

Energy Transition for Sustainable Development in Saudi Arabia: Renewable Energy Growth and Emission Reduction

Ali Q. Al-Shetwi*

Abstract

The Kingdom of Saudi Arabia (KSA) is undergoing a major shift toward sustainability under Vision 2030, targeting 58.7 GW of renewable energy (RE) by 2030 and major green hydrogen projects, such as NEOM's 4 GW plant, to cut oil use by 500,000 barrels daily and achieve net-zero emissions by 2060. This review provides a comprehensive analysis of KSA's energy transition, assessing the energy landscape, RE development, environmental impacts, and climate change mitigation efforts. Using a mixed-method approach, it combines quantitative assessments of energy consumption, RE capacity, and GHG emissions with qualitative insights into policy developments, technological advancements, and barriers. While KSA has made notable progress, existing studies often focus narrowly on specific technologies or sectors, lacking comprehensive analysis of recent initiatives, environmental trade-offs, policy updates, and regulatory frameworks. This review addresses these gaps by evaluating KSA's current energy mix, key drivers of energy transition, RE deployment progress, major projects, economic benefits, and climate strategies. The paper further examines environmental impacts, emissions profiles, and mitigation efforts while identifying major challenges, including infrastructure limitations, policy, and regulatory gaps, economic dependencies, socio-cultural factors, and technological constraints. Strategic recommendations are proposed to accelerate RE integration, improve energy efficiency, and strengthen climate mitigation efforts, emphasizing infrastructure investment, regulatory reform, innovation, and cross-sectoral collaboration. By offering an integrated and holistic perspective, this review aims to support policymakers, researchers, and industry leaders in navigating the complexities of Saudi Arabia's energy transition, contributing to broader global efforts toward climate resilience and sustainable development.

Keywords: Sustainable development, renewable energy, climate change, Saudi Arabia, emission reduction, carbon capture and storage

*Author for Correspondence

Ali Q. Al-Shetwi

E-mail: aalshetwi@fbsu.edu.sa

Department of Renewable Energy Engineering, Fahad Bin Sultan University, Tabuk, Saudi Arabia

Received Date: January 19, 2026

Accepted Date: January 28, 2026

Published Date: February 27, 2026

Citation Ali Q. Al-Shetwi. Energy Transition for Sustainable Development in Saudi Arabia: Renewable Energy Growth and Emission Reduction. International Journal of Renewable Energy and Its Commercialization 2026; 12(1): 31–70p.

INTRODUCTION

The global energy landscape is undergoing a profound transformation, driven by the urgent need to address climate change and achieve sustainable development. This transition involves shifting from fossil fuel-based energy systems to more sustainable, low-carbon alternatives such as renewable energy sources (RES) [1]. Globally, according to the International Renewable Energy Agency (IRENA) report published on March 26, 2025 [2], global renewable power capacity reached 4,448 GW by the end of 2024. Solar energy continued to lead the global total, accounting for 1,865 GW, maintaining its dominant position from the previous year. The

growth in renewable energy (RE) capacity is illustrated in Figure 1(a), while Figure 1(b) presents the International Energy Agency's (IEA) analysis outlining the global pathway to meet the 1.5°C climate target [3]. This trajectory aligns with the increasing deployment of RES. In line with this global energy transition, the KSA has adopted various measures to support and achieve its sustainability objectives. Saudi Arabia, traditionally known for its abundant oil reserves and heavy reliance on fossil fuels, is at a critical juncture in this transition. As of March 27, 2025, the country has recognized the importance of diversifying its energy mix and reducing its carbon footprint, as outlined in its Vision 2030 (V2030) initiative, which aims for 50% RE by 2030 and net-zero emissions by 2060 [4, 5]. This review paper explores the progress, challenges, and prospects of energy transition in Saudi Arabia, with a specific focus on RE development, environmental impacts, and climate change mitigation.

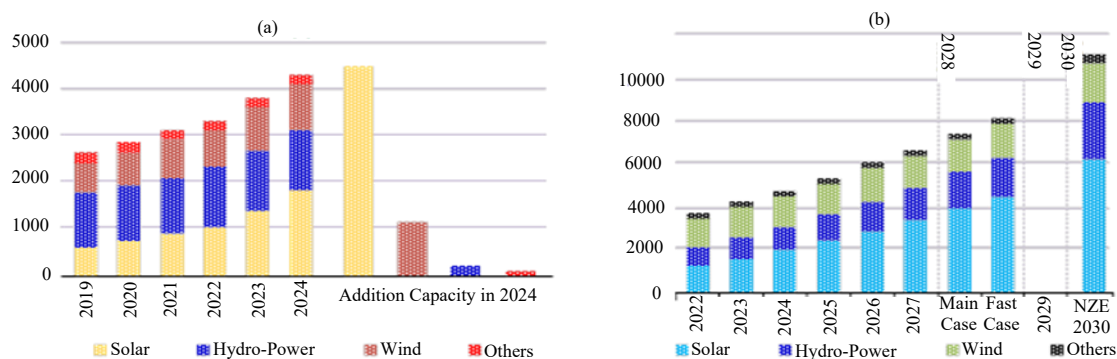


Figure 1. (a) Global growth in RE capacity (2019–2024); (b) Main, expedited, and Net Zero Scenario cumulative RE capacity.

Source: The data of Figure 1(a) and (b) are extracted from [2] and [3], respectively.

Previous studies have examined various aspects of energy transition in Saudi Arabia, providing valuable insights into specific areas. For instance, Belaïd and Al-Sarihi (2024) [6] analyzed the drivers and barriers of energy transition using a multi-level perspective approach, highlighting the role of economic factors [6]. Similarly, Salam & Khan (2018) and Zubair (2024) [7, 8] investigated the progress of solar energy development, emphasizing the potential and challenges of solar projects in the KSA. Other studies, such as Almasoud and Gandayh (2015) [9], have focused on the future of solar energy. Also, AlGhamdi et al. (2022) [10] highlighted the technical viability of wind energy in KSA, while Imam et al. (2024) and Suliman (2024) [11, 12] reviewed the opportunities and potential of both wind and solar energy, with particular emphasis on the promising prospects of solar PV systems. Additionally, Aldubyan and Gasim (2021) [13] analyzed the RE price reforms and their environmental implications. Moreover, Al-Shetwi et al. (2023) [14] evaluated the techno-economic potential of hybrid renewable systems in KSA. Literature on green hydrogen [15–17] underscores Saudi Arabia's competitive advantage in solar-driven electrolysis, particularly through flagship projects like NEOM's 4 GW electrolyzer. Al-Khelaiwi (2024) [18] also investigated Saudi Arabia's potential for producing green and blue hydrogen, along with an economic evaluation of both options. The existing literature on energy transition in Saudi Arabia has primarily focused on policy analysis, RE potential, and specific project developments. For example, [19] discussed future challenges in electricity supply and demand, while Amran et al. (2020) [20] examined sustainable energy policies for electrical conversion. More recent works, such as Al-Douri et al. (2019) [21], have assessed the potential contribution of renewables to electricity supply, and [22] examined the feasibility of reaching 30% of the energy mix by RES.

Furthermore, research on emissions mitigation, such as Kamboj et al. (2024) [23], outlines pathways for carbon capture and storage (CCS) and afforestation to achieve net-zero targets, but it lacks deep discussions on the initiatives leading this path in KSA. Similarly, Mir and Chang (2024) [24] focused on the environmental impacts on KSA's sectors but did not address the broader climate change mitigation strategies, such as carbon capture, utilization, and storage (CCUS), which are part of KSA's circular carbon economy program [25]. Review studies in the field of RE potential and impacts in KSA published

recently include progress for solar energy [7], deployment of RES with smart grid infrastructure [26], energy efficiency [27], RE production and V2030 [28], RE investment according to V2030 [29], RE contribution to power supply [30], potential for producing green hydrogen and hydrogen's role in mitigating climate change [31], CO₂ emissions along with energy consumption and economic growth [32, 33], as well as urbanization and RE in relation to environmental footprints [34]. However, these studies often focus on specific technologies or sectors; a comprehensive review that integrates RE development, environmental impacts, and climate change mitigation in the context of sustainable development is lacking. Also, these studies often lack a comprehensive view of the environmental and socioeconomic impacts of transition. In addition, an integrated analysis of the interplay between RE deployment, emission reduction, infrastructure, policy frameworks, and recent challenges is not sufficiently covered by previous studies. Moreover, the new initiatives of KSA, recent updates, status, progress, programs, economic benefits, investment, policy initiatives, current emissions profile, mitigation efforts, and regulatory frameworks toward energy transition and emission reductions are overlooked by much of the literature. Furthermore, existing reviews frequently overlook critical barriers and the environmental trade-offs of large-scale renewable projects, which impede large-scale adoption of sustainable practices. This fragmentation in the literature reveals a research gap in synthesizing a holistic perspective on Saudi Arabia's energy transition. These gaps hinder a holistic understanding of the energy transition and impede the development of comprehensive strategies to achieve Saudi Arabia's ambitious targets. Therefore, this review paper addresses this gap by providing an integrated analysis, examining Saudi Arabia's energy transition in a comprehensive manner. The contribution is in offering a unified perspective that can guide policymakers, researchers, and stakeholders in enhancing the effectiveness of energy transition efforts, particularly in the context of V2030 and net-zero targets by 2060. Based on the identified gaps and the scope of the review, the specific objectives are:

- To provide an overview of the current energy landscape and energy mix in Saudi Arabia and the drivers of its energy transition.
- To evaluate the potential, status, progress, development, initiatives, projects, key policies, economic benefits, and future directions of RE technologies and climate change in KSA.
- To assess the environmental impacts of the energy transition, including the current emissions profile and the role of current mitigation efforts and strategies like CCS, CCUS, and afforestation under V2030.
- To identify challenges and barriers to achieving a sustainable energy transition, including infrastructure needs, policy barriers, economic dependencies, socio-cultural barriers, regulatory hurdles, and technological gaps, and to propose future directions.
- To identify the current gap, propose recommendations, and provide actionable strategies for future energy transition efforts to enhance renewable integration and development, energy efficiency, and climate mitigation.

By addressing these objectives, this review aims to serve as a foundational resource for policymakers, researchers, investors, and industry leaders navigating the complexities of Saudi Arabia's energy transition, contributing to global efforts toward sustainable development and climate resilience.

OVERVIEW OF THE ENERGY STATUS IN KSA

Saudi Arabia has long relied on fossil fuels, with oil and natural gas dominating its energy landscape. Since the discovery of oil in the 1930s, the Kingdom has become the world's largest oil producer and exporter, with petroleum accounting for 90% of exports and nearly 75% of government revenue. The oil sector contributes about 42% of the GDP, while the private sector accounts for 40% [35]. In 2011, the country produced approximately 10.78 million barrels of petroleum per day, and as of recent data, Saudi Arabia holds 267.1 billion barrels of proven oil reserves (16% of the global share) and 6.3 trillion cubic meters of natural gas [36]. The Kingdom's energy sector remains heavily dependent on hydrocarbons, which account for 95% of its 92 GW electricity capacity – 60% from natural gas and 35% from oil. Rising domestic energy consumption, at 9.5 tons of oil equivalent per capita (three times the global average), alongside global decarbonization pressures, has spurred ambitious reforms under

V2030 [28]. The National Renewable Energy Program (NREP) aims to install 58.7 GW of renewable capacity by 2030, including solar, wind, and green hydrogen projects such as NEOM's 4 GW electrolyzer [37]. However, challenges persist, including \$30–40 billion in annual energy subsidies, 15% of oil used for desalination, and 672 million tons of CO₂ emissions as of 2022 [38]. Saudi Arabia has outlined a transition strategy to reduce reliance on oil, targeting 70% gas-based power generation by 2030, 17 GW of nuclear capacity by 2040, and a 28% reduction in energy demand through efficiency programs. These efforts align with its pledge to achieve net-zero emissions by 2060 [28, 38]. Installed electricity capacity grew from approximately 90 GW in 2020 to around 95 GW in 2022, yet renewables constituted just 0.4 GW, or less than 0.5% of total capacity. Electricity consumption has surged alongside economic growth. Recent data indicates consumption rose from 114, 161 GWh in 2000 to 298, 701 GWh in 2022. This increase has been predominantly met by fossil fuels, leading to per capita emissions four times higher than the global average [39].

Several factors drive Saudi Arabia's energy transition. V2030 aims to diversify the energy mix, with a goal of generating 50% of electricity from natural gas and renewables by 2030 while reducing liquid fuel dependence [4]. The Saudi Green Initiative [5] supports this transition by focusing on environmental sustainability and emission reduction. Global climate commitments, such as the Paris Agreement, further motivate these reforms, pushing the Kingdom to set ambitious targets for lowering emissions and increasing renewable energy adoption. Additionally, economic diversification plays a crucial role. Reducing reliance on oil revenues will help insulate the economy from price fluctuations and foster sustainable growth [40]. Through strategic investments in renewables and efficiency programs, Saudi Arabia seeks to balance its fossil fuel legacy with a sustainable future aligned with global decarbonization efforts. In 2022, for electricity generation, the sector remained heavily reliant on fossil fuels, with renewable capacity at a mere 0.4 GW, representing less than 0.5% of total capacity [41–45]. Table 1 highlights the targets and status of energy in KSA.

Table 1. The targets and status of energy in KSA.

Aspect	Target (2030)	Status
Total Energy Mix	50% gas, 50% renewables/nuclear	95% fossil fuels (60% gas, 35% oil), 5% others.
Electricity Generation	70% gas-fired, 30% renewables	95% fossil fuels (60% gas, 35% oil), less than 3% renewables.
Renewable Capacity	58.7 GW (solar, wind, hybrid)	2.8 GW (solar: 2.1 GW, wind: 0.4 GW).
Net-Zero Emissions	Interim: 278 MtCO ₂ reduction by 2030 -Zero net emission should be achieved by 2060	672 MtCO ₂ (2022 emissions).
Energy Efficiency	12% reduction in energy consumption	Energy intensity: 4,500 BTU/\$1 GDP (2021).
Hydrogen Production	4 GW green hydrogen (e.g., NEOM project with 1.2 million tons of green hydrogen)	Pilot projects underway (NEOM plant by 2026).
Nuclear Capacity	3.2 GW (2 reactors operational) and develop nuclear power capacity (plans for up to 17 GW by 2040)	0 GW (plans approved for construction).
Oil for Desalination	Reduce oil use by 50% (replace with gas)	15% of oil consumption powers are desalination plants.
Energy Subsidies	Phase out \$30–40 billion/year subsidies	Subsidies cost ~\$35 billion annually (2022).

POWER SECTOR AND ELECTRICITY GENERATION

Saudi Arabia's power sector is undergoing a significant transformation to align with V2030, focusing on diversifying its energy mix, improving efficiency, and increasing RE integration. The Kingdom's strategic investments aim to enhance sustainability, reduce reliance on fossil fuels, and modernize the electricity infrastructure to support growing demand.

Current Energy Mix and Generation Capacity

As of 2023, Saudi Arabia’s total electricity generation capacity was approximately 83 GW, with plans to expand it to 110 GW by 2028. The power sector remains heavily dependent on fossil fuels, with natural gas contributing over 60% and oil accounting for 30–40% of electricity generation. Figure 2 shows the electricity generation by source from 2000 to 2023 [46]. It can be seen that the generation from conventional sources dominates the power sector. RE, particularly solar, contributes less than 1%, highlighting the early stages of the country’s transition to cleaner energy sources. Based on the data published in IEA (2023) [45], Figure 3 illustrates the electricity generation trends over the past year, highlighting seasonal variations and peak demand periods. It provides a broader historical perspective, showcasing the evolution of electricity generation by source, including RES. The dominance of fossil fuels remains evident, though gradual shifts toward renewable sources are anticipated in the coming years [47].

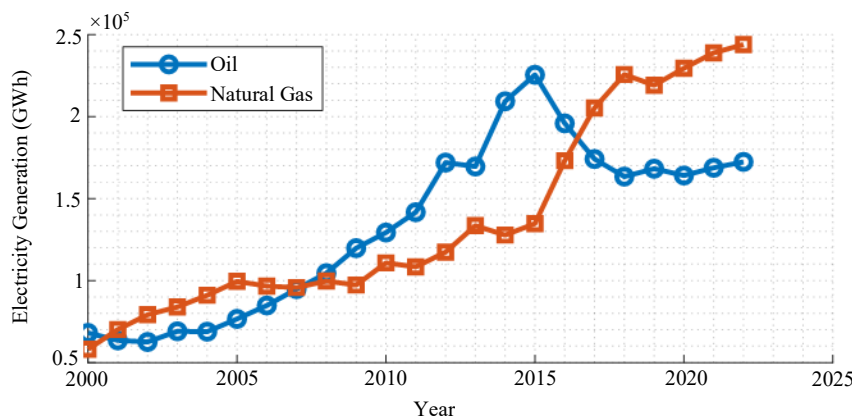


Figure 2. Electricity generation by source in Saudi Arabia (2000–2023).

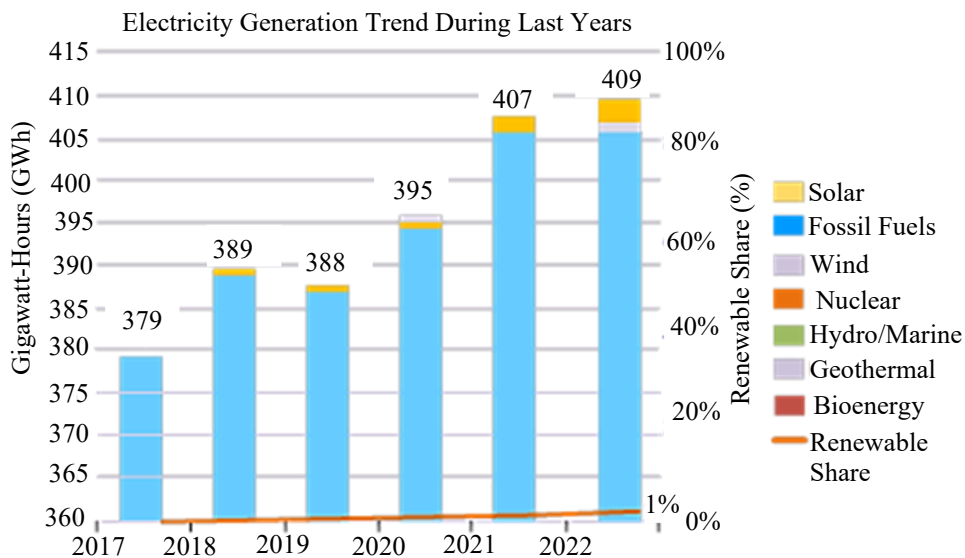


Figure 3. Electricity generation trend during the last year in KSA.
 Source: Based on data from [45].

The Saudi Electricity Company (SEC) plays a pivotal role in managing power distribution across the Kingdom, operating an extensive network comprising over 8,750 miles of transmission lines and 52,000 miles of distribution lines [46]. Over the past two decades, Saudi Arabia’s electricity production has experienced a remarkable surge, driven by economic expansion, population growth, and increasing industrialization. Figure 4 presents the total electricity production in Saudi Arabia from 2000 to 2022,

highlighting a consistent upward trajectory. Over this period, total electricity generation increased by approximately 232%, reaching 418, 839 GWh in 2022 [48]. Notably, the steepest growth occurred between 2010 and 2015, reflecting intensified infrastructure development and rising energy demand across residential, commercial, and industrial sectors. The trend suggests that Saudi Arabia’s energy sector has continuously evolved to meet escalating consumption requirements, supported by ongoing investments in power generation capacity.

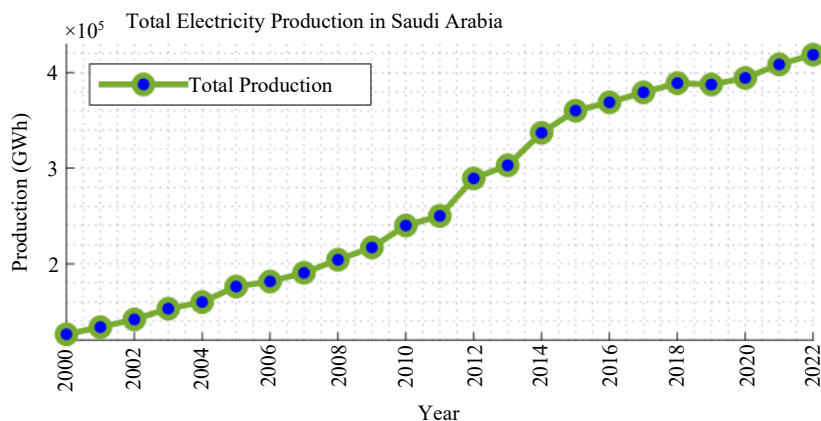


Figure 4. Total electricity production in Saudi Arabia in GWh.

Based on recent IEA data [49], Figure 5 compares Saudi Arabia’s electricity production regionally and globally. Within the Middle East, Saudi Arabia leads in generation, surpassing Iran and the UAE due to its large-scale power infrastructure, industrial growth, and high per capita consumption. Globally, the Kingdom ranks among the top producers when compared to countries with larger populations and industrial capacities such as India and Mexico.

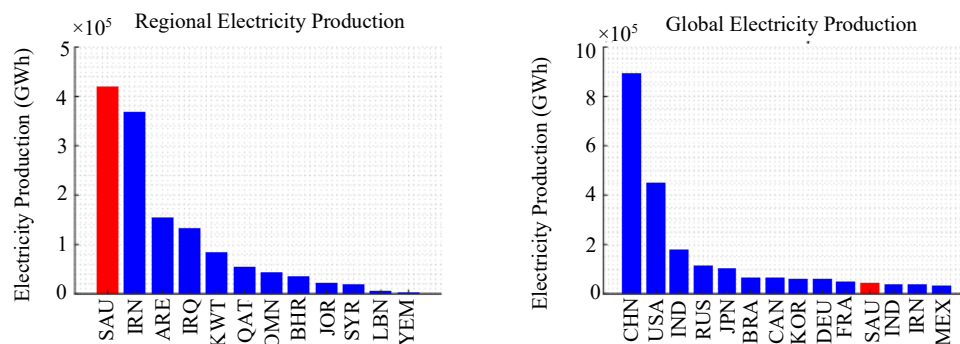


Figure 5. Total electricity production, regional, and global ranking.

Saudi Arabia ranks among the highest per capita electricity consumers globally, a consequence of its economic structure and extreme climatic conditions [48]. As depicted in Figure 6, electricity consumption per capita has shown a steady increase from 5.4 MWh in 2000 to approximately 10 MWh in 2023.

The demand for air conditioning, particularly during peak summer months when loads spike up to 40%, contributes significantly to this high consumption [46]. Additionally, population growth, urbanization, and industrial expansion have further driven electricity demand. Despite an overall upward trend, 2017–2022 shows a plateau, likely due to energy efficiency policies, economic shifts, and growing RE adoption. Stabilized per capita consumption may also reflect advancements in smart grids and demand-side management [50].

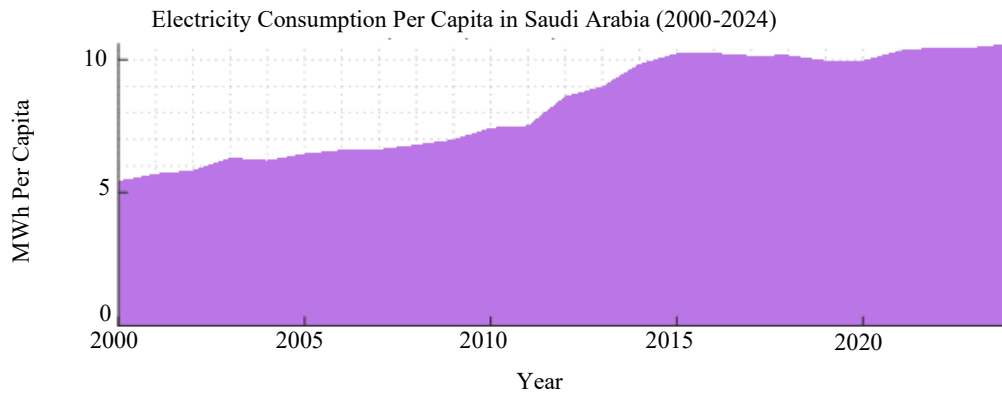


Figure 6. Electricity consumption per capita.
 Source: Adopted based on the statistical data of SEC.

Based on the recent KSA data [51] energy system, Figure 7 provides a breakdown of electricity use across different sectors. It can be seen that the electricity consumption in Saudi Arabia is primarily driven by the residential sector, which holds the largest share due to high cooling demands and appliance usage. While residential demand peaked around 2015, it has since stabilized with the adoption of energy-efficient technologies and regulations. The commercial and public services sector has steadily grown, reflecting business and government expansion, while industrial consumption surged between 2005 and 2015 before fluctuating due to energy pricing reforms and efficiency measures. The agricultural sector, though a small contributor, has seen gradual growth with increased mechanization. Other sectors maintain minimal consumption.

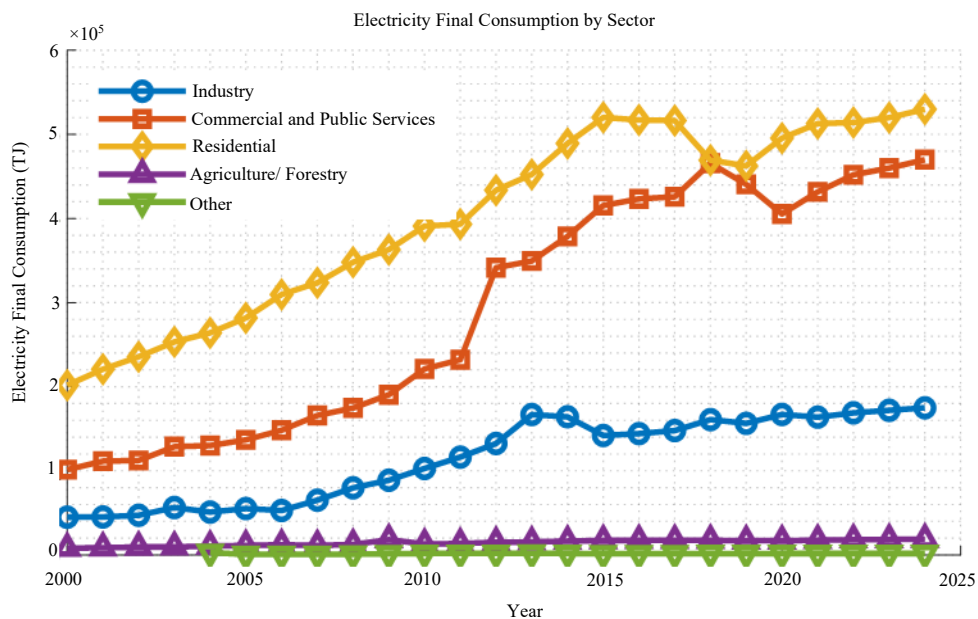


Figure 7. Electricity final consumption by sector in Saudi Arabia 2000–2024.

Saudi Energy Efficiency and TARSHID

Recognizing the importance of energy efficiency in sustainable energy development, Saudi Arabia established the Saudi Energy Efficiency Center (SEEC). The center aims to rationalize and enhance energy efficiency in both production and consumption to preserve natural resources and improve economic and social welfare [52]. Subsequently, SEEC launched the national Saudi Energy Efficiency Program (SEEP) to coordinate energy efficiency efforts across various sectors. The program focuses on three key sectors that consume over 90% of the country’s primary energy, as listed in Table 2 [53].

Table 2. Sector-wise oil and energy consumption.

Sector	Oil consumption per day	Share of total primary energy consumption
Industry	2.1 million barrels	46%.
Buildings	1.3 million barrels	29%.
Transportation	1 million barrels	20%.

In addition to SEEP, TARSHID, the National Energy Services Company, was established in 2017 as a fully owned subsidiary of the Public Investment Fund (PIF). TARSHID leads the energy efficiency sector in Saudi Arabia, driving national sustainability goals by achieving substantial energy savings. The company aims to develop the energy efficiency industry, attract international players and foreign investments, and create high-skilled jobs, contributing to Saudi Arabia's broader economic development goals. As Saudi Arabia transitions toward a more sustainable energy sector, the combined efforts of SEEC, SEEP, and TARSHID are expected to play a crucial role in optimizing energy consumption, reducing carbon emissions, and ensuring energy security for future generations.

Investment and Policy Initiatives in the Power Sector

Saudi Arabia has committed \$293 billion in investments for both conventional and RE projects by 2030, reinforcing its ambition to become a regional leader in sustainable power generation. The Kingdom is implementing energy efficiency programs, such as the SEEP, which aims to reduce overall energy demand by 28%. Additionally, the country is prioritizing the localization of the energy sector, promoting R&D and manufacturing renewable technologies to support job creation and economic diversification [53]. To ensure long-term sustainability, the Ministry of Energy is integrating smart grid technologies, automation, and digital transformation into the power sector [54]. These advancements aim to enhance grid reliability, reduce electricity losses, and optimize resource utilization. The government is also revising subsidy policies, addressing inefficiencies in energy consumption while ensuring fair economic returns for electricity providers.

RENEWABLE ENERGY IN KSA: POTENTIAL, CURRENT STATUS, AND FUTURE DIRECTIONS

This section provides a comprehensive analysis of RE in the KSA, focusing on green hydrogen production, solar energy, wind energy, other renewable sources, and energy storage technologies, with detailed insights into potential, economic benefits, status, and future directions.

Transition Towards Renewable Energy

Under V2030, Saudi Arabia aims to achieve a balanced energy mix, with 50% of electricity generated from renewables and the other 50% from natural gas. To accelerate this transition, the Kingdom is rapidly expanding its RE capacity, targeting 58.7 GW by 2030, comprising 40 GW from solar PV, 16 GW from wind energy, and 2.7 GW from concentrated solar power (CSP), as seen in Figure 8 [55]. By 2025, renewable capacity is expected to double to 12.7 GW, driven by key projects such as the 2.6 GW Al-Shuaibah solar plant and the 400 MW Dumat al-Jandal wind farm [56]. To support the integration of renewables and ensure grid stability, Saudi Arabia is heavily investing in large-scale energy storage solutions, with a goal of reaching 48 GWh of storage capacity by 2030. Major initiatives include the 2,000 MWh Bisha Project and a 12.5 GWh battery storage collaboration with BYD.

Additionally, the Liquid Fuel Displacement Program is actively working to replace oil-based electricity generation with cleaner alternatives, reducing reliance on fossil fuels and enhancing environmental sustainability. The government has also allocated significant land resources for RE development, including 1,862 sq km for solar projects and 260 sq km for wind energy installations, reinforcing its commitment to a sustainable energy future [57]. Saudi Arabia plans to invest \$270 billion in low-carbon energy by 2030 [58]. Table 3 lists key Saudi energy transition investments toward sustainable and RE systems.

Table 3. Key investments in Saudi Arabia’s energy transformation and RE programs.

Initiative/project	Sector/resource focus	Investment amount	Ref.
NEOM initiative	Aiming to establish a fully renewable-powered city	\$500 billion	[59].
Green Economy Investment under SGI programs	Various sustainability-driven initiatives within the green economy	700 billion SAR (~\$187 billion USD)	[58].
Renewable energy programs targeted for 2030	Expansion of renewable energy, including solar and wind power	\$30 billion to \$50 billion	[57].
King Salman Energy Park (SPARK) development	Industrial growth in the energy sector	\$1.6 billion	[60].
Solar energy industry initiatives	Development and expansion of the solar energy sector	Multi-billion-dollar investment	[59].
Saudi Aramco’s restructuring of industrial projects	Transitioning the oil and gas sector toward sustainable operations	\$30 billion	[37].
Planned SPARK investments over the next two years	Advancing the energy sector, emphasizing innovation and development	More than \$2 billion	[60].
Government-backed renewable energy projects	Attracting private investment in renewable energy initiatives	5.2 billion SAR (~\$1.4 billion USD)	[59].
NEOM Green Hydrogen Project	Renewable energy, green hydrogen and ammonia using solar/wind	\$8.4 billion	[17, 61, 62].
PIF Energy Solutions Co.	Potential multiple green hydrogen projects	\$10 billion	[59, 62, 63].
Waad Al-Shamal Wind Farm	Renewable energy, wind power generation	\$980 billion	[64].
The Solar PV Cell & Module Manufacturing Plan	Manufacturing of PV panels	\$186.6 million	[59].

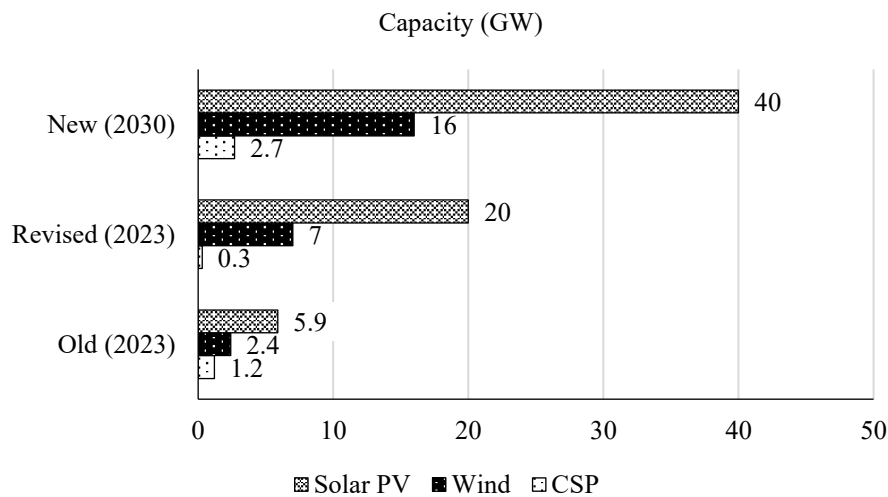


Figure 8. Saudi Arabia renewable energy targets.

The transition to RES is evidenced by significant trends in capacity, efficiency, and investments. As shown in Figure 9, per capita renewable capacity increased sharply from approximately 3 W/person in 2020 to around 10.9 W/person by 2021, maintaining that level into 2022, as reported by IEA (2024) [3]. This reflects accelerated RE deployment in response to energy transition targets. Figure 10 shows capacity utilization rates in 2022, where wind energy leads with 89%, indicating high operational efficiency. In contrast, solar shows lower utilization at 32%, while fossil fuels remain moderate at 56% [45]. These differences underline the reliability and maturity of specific renewable technologies in various regions and climates.

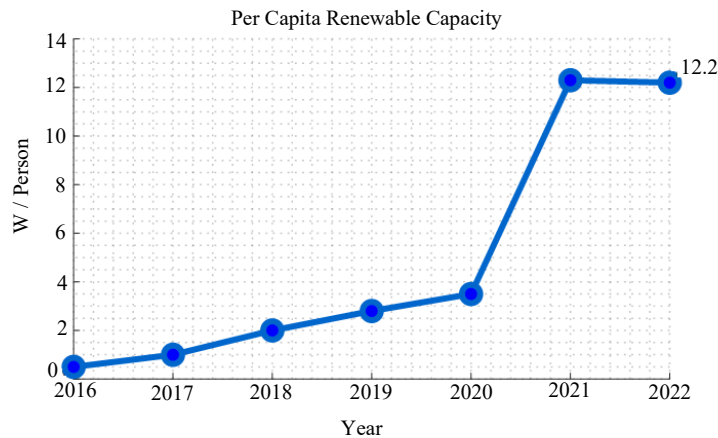


Figure 9. Growth in per capita renewable capacity in Saudi Arabia (2016–2022).

Figure 11 illustrates net capacity change, which shows a notable shift. From 2018 to 2023, renewables steadily gained capacity, peaking at 2.1 GW in 2023, while fossil fuel capacity changes fluctuated, with a major drop of -3.5 GW in 2018 and a rebound to 5.6 GW in 2022 [45, 46]. This indicates growing renewable integration despite intermittent fossil fuel investments, highlighting a transitional phase toward cleaner energy systems.

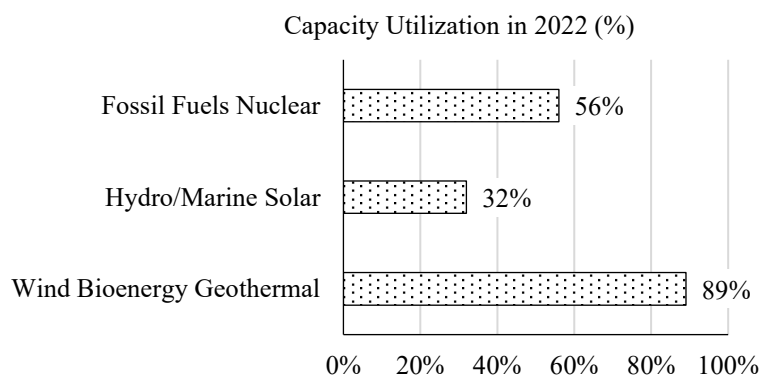


Figure 10. Percentage capacity of energy generation in 2022.

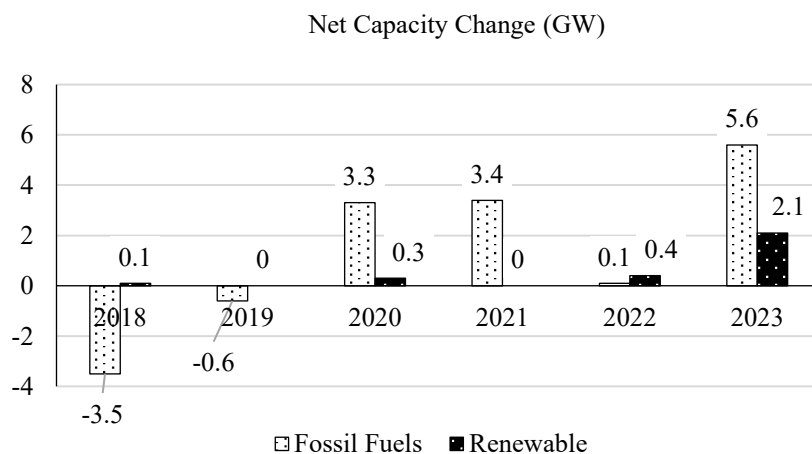


Figure 11. The net capacity change in KSA energy sector.

In general, Saudi Arabia’s evolving RE landscape emphasizes its nascent but growing shift from fossil fuels. Regarding the RE share in 2023, solar dominates the renewable mix at 87% (2.4 GW), followed by wind at 13% (0.4 GW), while hydro, bioenergy, and geothermal remain negligible (0%), as shown in Figure 12.

This reflects Saudi Arabia’s strategic focus on solar, leveraging its world-class irradiance (2, 200–2, 500 kWh/m²/year), while wind projects, like Dumat al-Jandal (400 MW), mark early diversification efforts. Finally, the high trend in capacity installed is shown in Figure 13. Fossil fuels (oil and gas) still dominate, accounting for ~97% of the 92 GW total capacity in 2023. Renewables grew modestly from 3% (2016) to ~3% (2023), equivalent to 2.8 GW, underscoring slow initial progress. However, recent acceleration is evident with 5.1 GW under construction (e.g., Sudair Solar 1.5 GW, Al-Shuaibah 2.6 GW) [65].

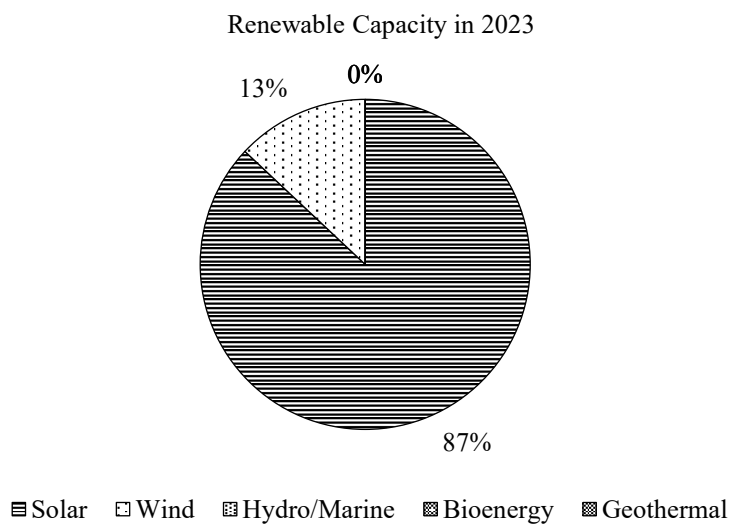


Figure 12. The share of renewable energy in KSA, 2023.

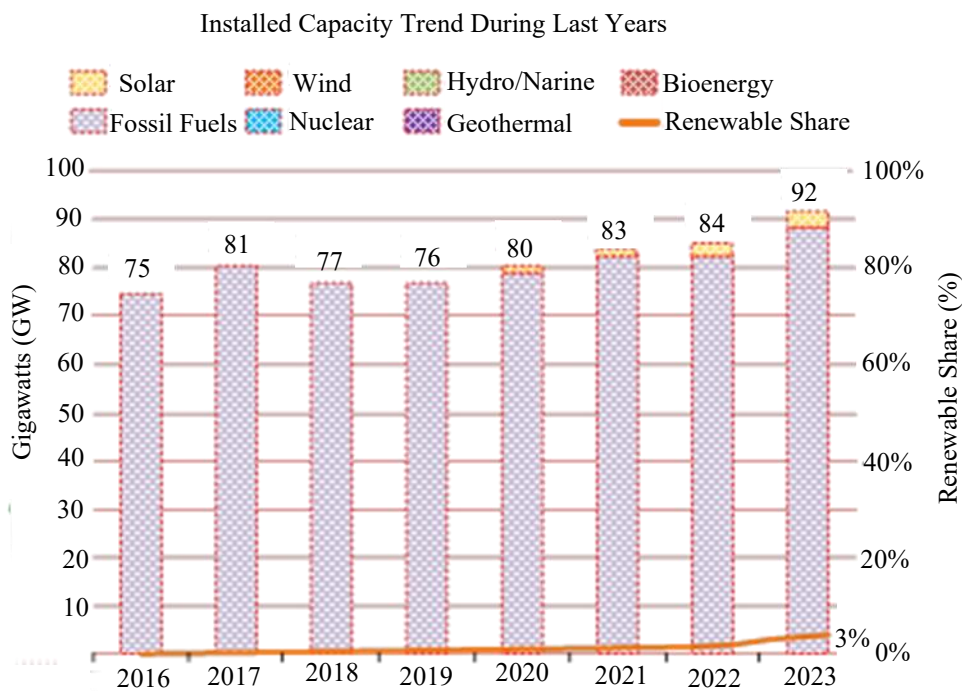


Figure 13. The installed capacity trend of the energy sector in KSA over the previous few years.

Green Hydrogen Production In KSA

The production of green hydrogen has gained significant traction, particularly in countries abundant in RESs such as Saudi Arabia. This process involves using renewable electricity from sources, like solar, wind, or hydropower, to split water molecules into hydrogen and oxygen [66]. Unlike grey or blue hydrogen, green hydrogen is an eco-friendlier alternative, as it does not produce carbon dioxide emissions. Saudi Arabia possesses significant potential for green hydrogen production, primarily due to its vast solar energy resources. The nation's substantial investments in RE and ambitious sustainability goals reflect its commitment to a greener future. Additionally, its extensive desert landscape provides ideal locations for large-scale solar farms. One of the key advantages of green hydrogen production is its capability to store RE, which is particularly beneficial in Saudi Arabia, where energy demand surges during the summer months. By producing and storing excess solar energy, green hydrogen can be utilized during peak demand periods, ensuring a stable and efficient energy supply [67]. Green hydrogen, produced via electrolysis using RE, is pivotal for KSA's decarbonization strategy. Saudi Arabia aims to establish itself as a global leader in hydrogen production, leveraging its competitive cost structure and rich natural resource base to gain a strong foothold in the international market. By the year 2020, both government entities and private sector companies in the Kingdom had collectively committed over \$900 million toward the development of hydrogen-related initiatives. Through visionary initiatives, like NEOM and substantial investments in RE, Saudi Arabia aspires to become a leading force in the global hydrogen market [68]. A critical component of realizing this ambition lies in the development of comprehensive infrastructure for green hydrogen production. This encompasses the establishment of RE facilities, robust transportation systems, and adequate storage solutions. Figure 14 illustrates the technological framework underpinning green hydrogen production within the NEOM project. The NEOM Green Hydrogen Project, a joint venture by NEOM, ACWA Power, and Air Products, is set to be the world's largest, with a 4 GW renewable capacity producing 600 tons of green hydrogen daily by 2026, saving 5 million tons of CO₂ yearly. Other projects are in early stages, targeting 2.9 million tons annually by 2030 and 4 million by 2035, leveraging KSA's solar and wind.

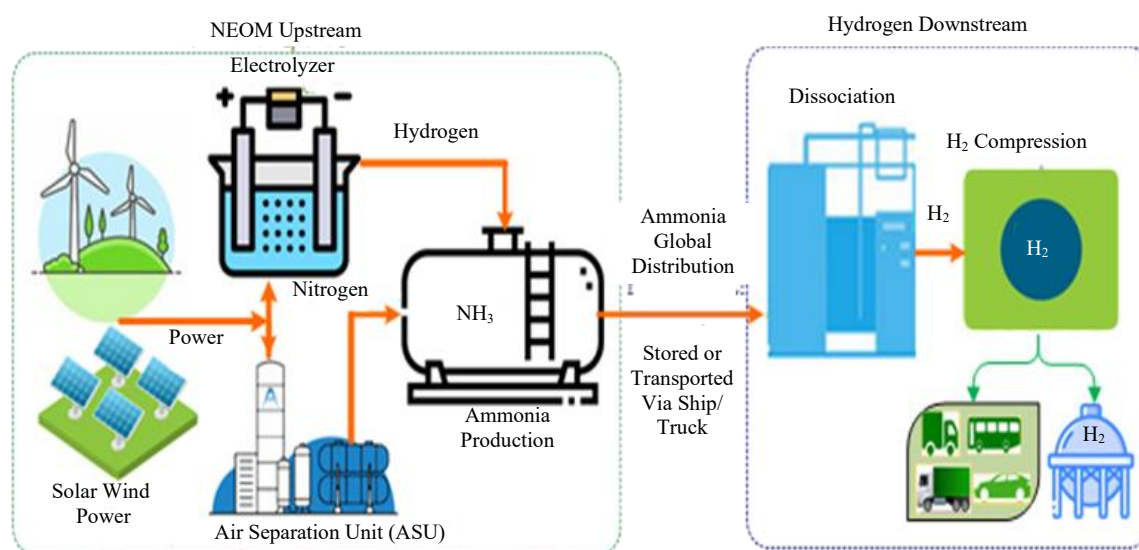


Figure 14. Hydrogen generation in KSA for the NEOM initiative.

In terms of literature studies, a simulation study was conducted on NEOM City to stabilize a grid powered exclusively by solar and wind energy, utilizing hydrogen storage. The analysis modeled a 50/50 solar-wind energy mix and found that with a 30 GW renewable capacity, an annual dispatchable energy contribution of 60 TWh could be achieved.

This would require 8 TWh of hydrogen storage, 22 GW of electrolyzer capacity, and a 13.5 GW hydrogen power generation facility. Additionally, integrating high-efficiency storage systems, such as flow batteries, could reduce the required electrolyzer power capacity by up to 80%. Table 4 shows the energy and power of hydrogen storage in NEOM City.

According to Al-Khelaiwi et al. (2024) [18], the levelized cost of hydrogen (LCOH) has been evaluated for both green hydrogen (GH) and blue hydrogen (BH). Among various cities in Saudi Arabia, NEOM – utilizing an energy mix of 50% wind and 50% PV – achieves the lowest LCOH for GH at \$3.27/kg, significantly lower than the highest value reported, which is \$12.17/kg. A study [69] analyzed the potential of solar energy for hydrogen production in NEOM, highlighting the region’s favorable solar conditions. With an average annual solar radiation of 12.54 GJ/m², NEOM presents a strong opportunity for green hydrogen generation. The study found that solar-powered hydrogen production could achieve a rate of 41–47 moles/day/m², demonstrating its viability as a sustainable alternative to fossil fuels. This reinforces NEOM’s potential as a hub for RE and hydrogen-based solutions.

Table 4. Energy and power of hydrogen storage in NEOM City.

Station	Share wind-solar	Solar and wind power	Annual energy dispatch	Annual energy non-dispatch	Electrolyzer (EL) power	Energy storage (ES)	ES to EL dispatch	EL to annual energy dispatch
Neom city lower	20–80	24 GW	51 TWh	63 TWh	15 GW	21 TWh	0.412	0.924 (GW/TWh).
Neom city upper	20–80	30 GW	64 TWh	79 TWh	19 GW	26 TWh	0.406	0.297 (GW/TWh).
Neom city 30GW	50–50	30 GW	60.09 TWh	84.42 TWh	22.3 GW	8.13 TWh	0.35	0.371 (GW/TWh).
Neom city 1GW	50–50	1 GW	2.003 TWh	2.841 TWh	0.743 GW	0.271 TWh	0.35	0.371(GW/TWh).

Saif et al. (2025) [70] conducted a techno-economic analysis of solar-powered green hydrogen production in Dhahran, Saudi Arabia, comparing CSP, PV, and hybrid PV-CSP systems for a 1 MW solid oxide electrolyzer cell. The PV system proved most cost-effective, with lower electricity (5.33¢/kWh vs. 8.54¢/kWh for CSP) and hydrogen production costs (\$4.23/kgH₂ vs. \$4.95/kgH₂ for CSP).

The hybrid system had an intermediate cost of \$4.57/kgH₂. CSP, however, had lower GHG emissions (10.8 vs. 35.4 gCO₂eq/kWh for PV) and required less land. Solar-based hydrogen production could cut CO₂ emissions and generate up to \$22.9 million in carbon credits. Another study [71] indicates that green hydrogen currently ranks third in economic competitiveness among hydrogen production methods, with an estimated cost of \$2.16/kg. However, it is projected to experience the most significant cost reductions in the coming decades, driven by declining prices of electrolysis technologies and renewable electricity [72].

Based on KAPSARC reports [73], several proposed solar projects in the Kingdom aim to achieve tariffs below this threshold, suggesting the potential for even lower production costs.

Should RE prices fall to \$13/MWh by 2030, the cost of green hydrogen could decrease to approximately \$1.48/kg (Figure 15). Further reductions – to below \$1/kg – may be achievable by 2050 if electrolyzer costs decline to \$400/kW and renewable electricity prices drop below \$10/MWh. These developments could lead to a 31% reduction in hydrogen costs by 2030 and a 53% reduction over the long term (Figure 16).

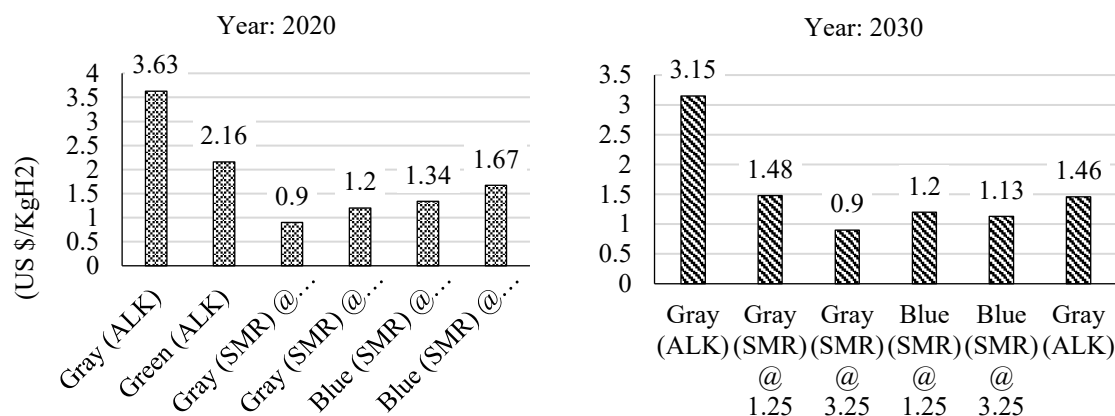


Figure 15. Current and projected costs of hydrogen production (US\$/kgH₂) in KSA. Source: Adopted based on KAPSARC’s data.

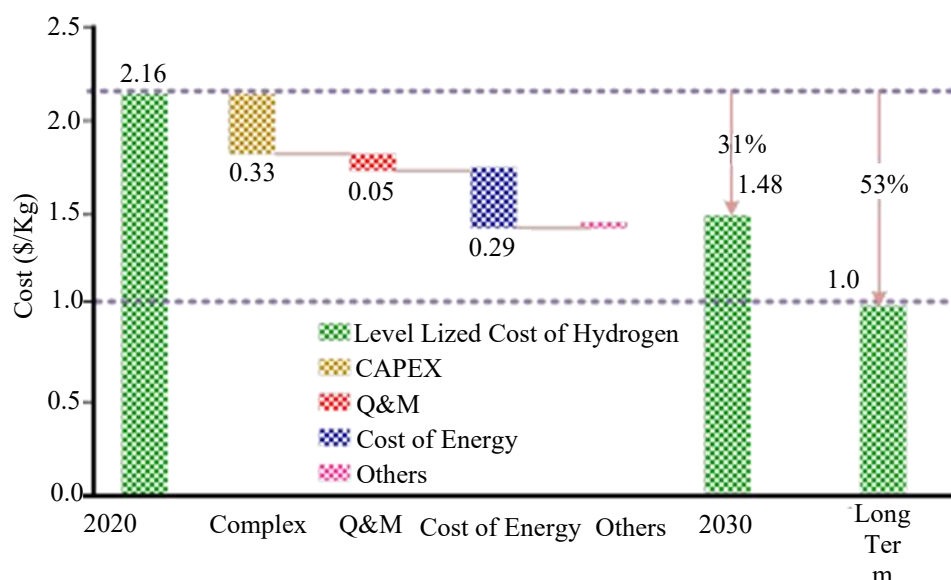


Figure 16. Anticipated decreases in cost of production for green hydrogen. Source: Adopted based on KAPSARC’s data.

It is important to mention that the production of blue, grey, and turquoise hydrogen in Saudi Arabia does not align with sustainability goals as strongly as green hydrogen. While the country is still in the planning phase for utilizing these hydrogen types, grey hydrogen, in particular, remains part of its current energy strategy. However, as Saudi Arabia aims to reduce carbon emissions and transition toward cleaner energy sources, the focus is gradually shifting toward green hydrogen. Blue and turquoise hydrogen may play a transitional role, leveraging the country’s natural gas resources while carbon capture technologies develop further. Challenges include high costs and infrastructure needs, but KSA’s location and resources position it as a potential global hub.

Solar Energy

Saudi Arabia spans approximately 2.25 million km², characterized by a desert climate with extreme temperatures and minimal rainfall, except in the southwestern highlands, which feature a semi-arid climate. The country receives an average daily solar irradiation of 6 kWh/m², with annual values ranging from 2000 to 2400 kWh/m² (among the highest globally), depending on the region, and boasts 80–90% clear sky days annually [74]. Temperatures vary widely, from scorching summer highs exceeding 40°C in central and eastern areas to milder conditions in the highlands and coastal regions. This variability

impacts solar energy potential and system efficiency, necessitating region-specific data for planning RE projects. Table 5 shows the solar irradiation and average temperature by region in KSA. Saudi Arabia's regions exhibit high solar irradiation, averaging 6.1 kWh/m²/day, with Makkah leading at ~2400 kWh/m²/year and Dammam slightly lower at ~2,340 kWh/m²/year. Temperatures range from 20°C in Abha to 33.6°C in Riyadh, impacting PV performance [75]. The Saudi Arabian solar PV power potential map is shown in Figure 17. The map highlights Saudi Arabia's substantial solar potential, particularly in its northeastern (e.g., Tabuk) and mid-eastern coast cities; locations, like Khamsi Mushayt, Najran, Jeddah, and Mecca, have great potential for solar PV systems. These high irradiation values position these locations as prime candidates for large-scale solar energy generation. Harnessing this potential could significantly reduce the Kingdom's reliance on fossil fuels and contribute to lowering carbon emissions.

Table 5. Solar irradiation and average temperature by region in KSA.

Region	Solar irradiation (kWh/m ² /year)	Solar irradiation (kWh/m ² /day)	Average temperature (°C)
Riyadh (Central)	2,250–2,300	6.1–6.3	~33.6.
Makkah (Western)	2300–2400	6.4–6.7	~30.0.
Dammam (Eastern)	2,250–2,340	6.2–6.4	~30.0.
Abha (Southwestern)	2,050–2100	5.6–5.8	~20.0.
Tabuk (Northwestern)	2250–2300	6.0–6.3	~25.0.
Najran (Southern)	2,200–2300	6.1–6.3	~27.0.
Khamis Mushait (Southwestern)	2,050–2200	5.9–6.0	~21.0.
Hafr Al-Batin (Northeastern)	2,200–2,280	6.0–6.2	~28.0.

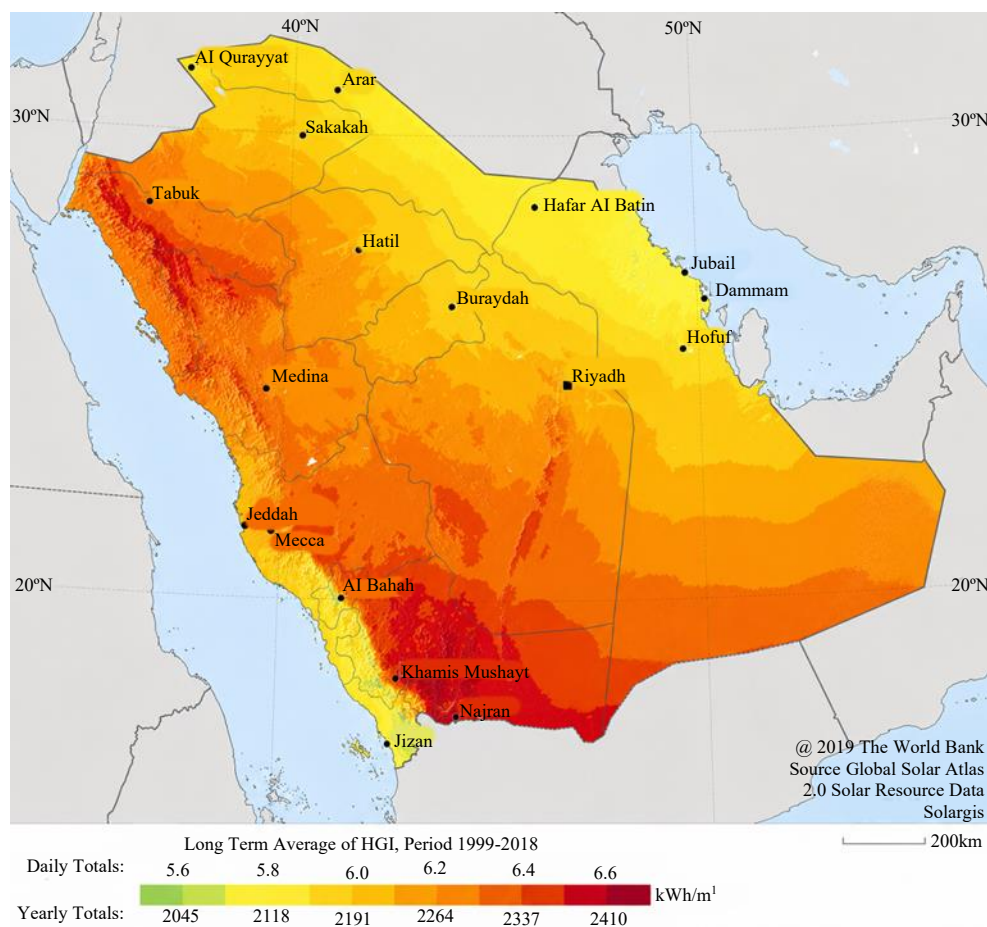


Figure 17. Saudi solar PV potential.

Solar energy is the backbone of KSA's renewable strategy, given its location in the sun belt with over 2,000 hours of sunshine annually [74]. Current installed capacity reached 2.8 GW by 2023, with significant projects like the Sudair Solar PV Plant at 1.5 GW, one of the largest globally, powering 185,000 homes and offsetting 2.9 million tons of emissions yearly [76]. The Sakaka solar PV project operates under a 25-year power purchase agreement (PPA) with the Saudi Power Procurement Company (SPPC), featuring one of the world's lowest solar tariff rates – 0.08872 SAR/kWh (approximately USD 0.024/kWh). With an installed capacity of 300 MW and spanning an area of 6 square kilometers, the project is designed to generate approximately 680 GWh of electricity annually. This output is sufficient to meet the energy needs of nearly 75,000 households [77]. Challenges include land use and water for panel cleaning, but costs are competitive, with Sudair at \$0.01239/kWh.

As of 2024, installed solar capacity stands at ~4.3 GW, with: (a) Sakaka Solar Plant: 300 MW (operational since 2021, powering 75,000 homes); (b) Sudair Solar PV: 1.5 GW (under construction, set to reduce CO₂ by 2.9 million tonnes/year); and (c) Al-Shuaibah Solar: 2.6 GW (world's largest single-site solar project, commissioning in 2025). Other main solar PV projects in KSA are listed in Table 6 [77]. In terms of the best solar locations in KSA, Suliman (2024) [12] identified northwestern Saudi Arabia, particularly Tabuk, as an ideal location for solar farms due to high solar irradiance of 6.5 kWh/m²/day and minimal dust accumulation. However, dust mitigation remains crucial, as uncleaned panels can suffer up to a 20% efficiency loss. NREL Analysis (2021) estimated the country's technical solar potential at 1,470 TWh/year, more than 500 times its current generation. To manage solar intermittency, hybrid solar-plus-storage systems were recommended, with projected leveled costs between \$13–18/MWh by 2030. The IRENA report praised Saudi Arabia's solar auction successes, citing record-low bids such as \$10.4/MWh (1.04 US cents/kWh) for the 600 MW Al-Faisaliah Solar project. However, it warned that large-scale solar farms, requiring around 3.5 acres per MW, could create land-use conflicts with urban and agricultural expansion. A feasibility study conducted in [78] highlighted that solar-powered desalination projects, such as Jubail 3A, could help save up to 1.5 million barrels of oil per day by 2030. To summarize, beyond the listed initiatives, several new projects have been announced, notably under the NREP, which is backed by the Public Investment Fund (PIF) and aligns with the Ministry of Energy's goals.

Table 6. Summary of main solar energy projects in KSA.

Project	Capacity	Location	Announcement date	Expected operational year
Sakaka Solar PV	300 MW	Al Jouf Province	2018	2021 (Operational)
Sudair Solar PV	1.5 GW	Riyadh Province	2021	2024
Ar rass 1	700 MW	Qassim Province	–	2025
Ar rass 2	2 GW	Qassim Province	2023	2026
Al-Shuaibah Solar	2.6 GW	Mecca Province	2023	2025
Al-Kahfah solar project	1.42 GW	Eastern Province	2023	2026
Tabarjal	400 MW	Al Jawf Province	2022	2026
Amaala solar project	250 MW	Tabuk Province	2023	–
Saad 2 Solar PV Park	1.125 GW	Central Province	2023	2026
Al Sadawi Solar	2 GW	Eastern Province	2024	2025–2026
Al Masa'a Solar	1 GW	Hail Province	2024	2025–2026
Al Henakiyah II Solar	400 MW	Medina Province	2024	2025–2026
Haden PV Plant	2 GW	Mecca Province	2024	2027
Rabigh II Solar	300 MW	Rabigh Industrial City	2024	2025–2026
Al-Mowayh Solar PV Plant	2 GW	Mecca Province	2024	–
Al-Faisaliah Solar	600 MW	Riyadh Province	2023	2026
Jafurah Solar	2.5 GW	Eastern Province	2024	2027
Yanbu Solar	700 MW	Medina Province	2022	2028
NEOM Solar Park	3.4 GW	Tabuk (NEOM)	2022	2030

However, residential solar PV adoption remains slow due to subsidized grid electricity, making large-scale integration challenging. Additionally, efficiency reductions of 15–25% annually due to dust and extreme heat are another challenge [79]. Moreover, grid integration requires major investment in upgrades to accommodate solar variability. The future outlook targets 40 GW of solar capacity by 2030, expected to supply about 20% of national electricity demand. The NEOM project plans a 3.4 GW solar park to power its \$500 billion megacity, while V2030 has allocated \$30 billion to solar projects, including the 2.2 GW Helios green hydrogen initiative.

Wind Energy

Saudi Arabia has strong wind energy potential, especially in the western and southwestern regions [80]. Figure 18 shows a GIS-based wind speed map (based on 39 years of data from 46 stations nationwide), highlighting key areas suitable for wind energy development [81]. It shows an interpolated wind resource map classified into nine categories, with wind speeds at 50 m AGL ranging from 3.7 to 6.4 m/s. The top two classes (5.8–6.4 m/s) are ideal for wind farm development. These high-potential areas are mainly in the eastern and central regions, with smaller zones along the northern border and parts of the southern-north coast. The southern coastal area, with wind classes 1–5 (below 5 m/s), generally lacks viable wind resources. According to Hassan et al. (2023) [31], the western and southwestern regions of the country have the highest wind power density, with some areas having a wind power density of over 500 W/m². Cities, such as Jeddah, Mecca, Taif, and Abha in these regions, have the potential to produce substantial amounts of wind energy.

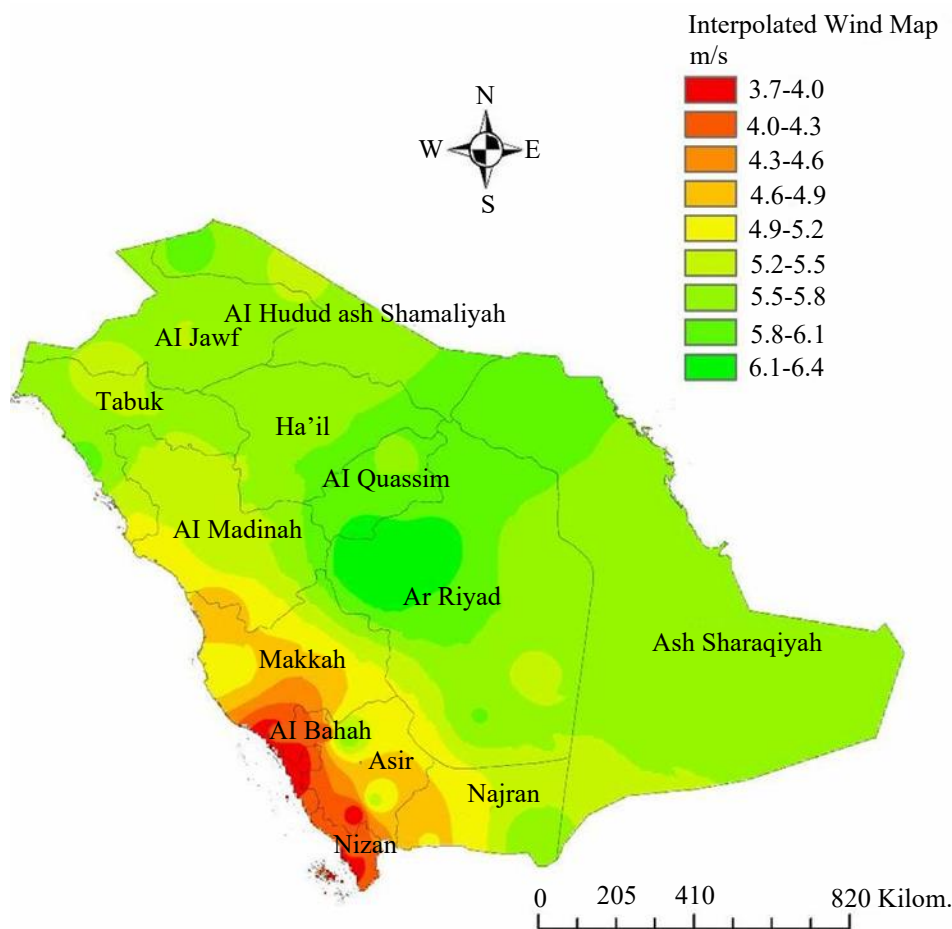


Figure 18. Potential wind speed in Saudi Arabia (GIS map).

The wind speed and pressure data for different locations are summarized in Table 7. Based on the global wind atlas data [82], Figure 19 shows the mean wind speed across KSA stations at a 100 m

height, which ranges from 8.46 m/s (top 2% windiest areas) to 6.57 m/s (covering 100% of regions), demonstrating a gradual decline with broader coverage. Notably, the top 20% of areas (≥ 7.63 m/s) are highly suitable for wind energy, as speeds consistently exceed the 6.5–7 m/s threshold required for commercial turbines. Even the least windy regions (100% coverage) maintain speeds above 6.5 m/s, indicating widespread wind energy potential nationwide.

Table 7. Wind speed and pressure data for stations in Saudi Arabia [10, 28, 83].

Station	Min wind speed (m/s)	Max wind speed (m/s)	Mean pressure (mb)
Khamis	3.14	12.9	797.9
Qaisumah	3.55	11.8	969.5
Gassim	2.78	9.3	937.6
Al-Wejh	4.43	11.8	1007.90
Dhahran	4.38	11.8	1006.70
Hail	3.24	10.8	901.3
Tabouk	2.73	15.5	926.0
Abha	2.94	14.9	794.0
Gizan	4.22	16.5	954.8
Jeddah	3.71	11.3	1007.30
Yanbu	4.33	14.4	916.9
Bisha	2.47	10.3	884.0
Rafha	3.86	12.4	960.3
Al-Jouf	4.02	15.9	936.1
Talf	3.66	10.3	855.4
Riyadh	3.09	8.8	942.4
Nejran	2.10	8.8	879.4
Arar	3.61	12.9	949.6
Turatif	3.76	10.3	1007.80

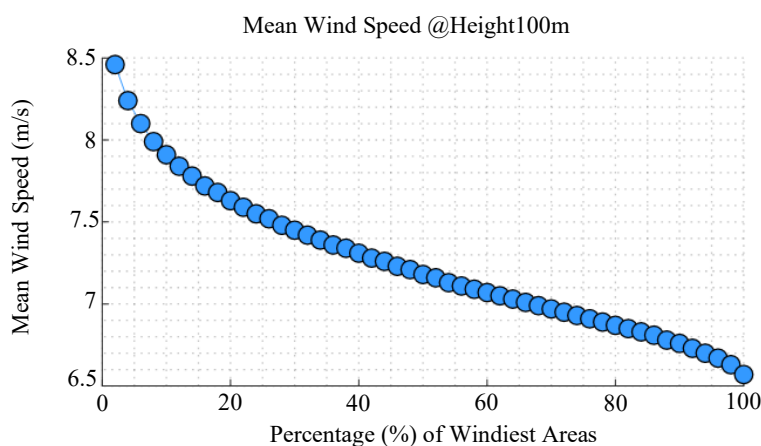


Figure 19. Mean wind speed at 100 m height in KSA.

Source: The figure is adopted based on data from [82].

Winds in KSA are most frequent from the north/northeast (30° – 60°) and northwest (300° – 360°), with frequencies of 10–11% per sector, while southerly winds (210° – 270°) are the least common (5–7%). This bimodal pattern reflects seasonal influences such as winter Shamals (northwesterly) and summer monsoons (northeasterly). For optimal energy capture, turbines should be oriented toward these dominant directions, particularly in high-wind-speed regions identified in Figure 20 [82].

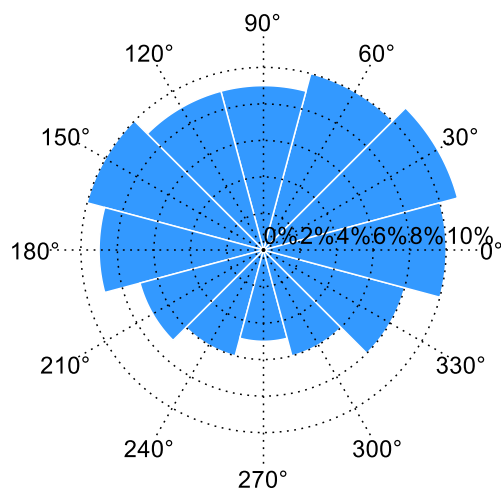


Figure 20. Wind frequency rose in Saudi Arabia.

Source: The figure is adopted based on data from [82].

Wind energy, though smaller in scale, is growing, with the Dumat Al Jandal Wind Farm at 400 MW, commissioned in 2021, marking KSA’s first utility-scale wind project and the largest in the Middle East, with a cost of around €12.5 million (\$14 million or SAR 52.4 million). Wind potential is assessed in northern and coastal regions, with targets for 16 GW by 2030, including onshore and potential offshore projects. Challenges include grid connectivity and higher costs compared to solar, but studies show suitability for small-scale hybrid applications [84].

Other Renewable Sources

Beyond solar and wind, KSA explores other renewables, though they are less developed. Geothermal energy holds significant potential in Saudi Arabia, particularly along the Red Sea, where recent studies have identified numerous hot springs and volcanic regions [85]. One of the most notable geothermal sites is the Wadi Al-Lith area (Ain Al-Harrah), located near the Red Sea coast. This region is geologically active, shaped by tectonic movements and subsurface hydrothermal systems, making it one of the most promising geothermal structures in the country [86]. Additionally, recent studies have reported subsurface temperatures ranging from 150°C to 300°C in areas, such as Jizan, Arar, Al Lith, and Tabuk, indicating favorable conditions for geothermal energy production (see Table 8). Despite these promising resources, no geothermal power plants have been constructed or commissioned in the Kingdom to date, with potential for 1 GW by 2030.

Table 8. Geothermal energy sources in KSA: Regional distribution and temperature ranges [87].

Location	Region	Temp. (°C)
Al-Lith	Makkah Region	40–90
Jizan	Jizan Region	50–120
Al-Khoba	Southern Borders	30–70
Harrat Rahat	Madinah Region	175–200
Harrat Lunayyir	Tabuk Region	60–100
Al-Hasa Oasis	Eastern Province	25–50
Najran	Najran Region	40–80
Harrat Khaybar	North of Medina	70–150

In terms of waste-to-energy (WtE), Saudi Arabia has significant potential for WtE development, supported by the availability of various waste resources such as municipal waste (24%), wood waste (64%), landfill gas (5%), and agricultural waste (5%) [85]. The use of conventional biomass for energy

remains extremely limited due to the country's arid climate, scarce forest resources, and low dependence on traditional biomass sources such as wood, crop residues, and animal dung [88]. WtE targets 3 GW, with small-scale pilots, like Riyadh's 5 MW plant and planned Jeddah facilities, backed by \$1–2 billion in investments [89]. According to the IEA, biomass contributes less than 0.1% to Saudi Arabia's total energy supply, highlighting a largely untapped opportunity for RE integration through WtE technologies. However, hydroelectricity is limited due to the arid climate.

Energy Storage Technologies for Renewable Energy Integration in KSA

Energy storage is critical for integrating intermittent renewables, with KSA investing in battery energy storage systems (BESS). A notable project is the 12.5 GWh battery storage deal with BYD, part of a 15.1 GWh total, supporting Vision 2030 by stabilizing the grid and managing peak demand [90]. The Saudi Power Procurement Company (SPPC) launched a 2 GW/8 GWh BESS tender, with pre-qualified bidders including Masdar and ACWA Power, aiming for completion by 2026. Technologies include lithium-ion and emerging sodium-ion batteries, with pumped hydro and hydrogen storage under consideration, which are essential for grid reliability [91].

The current landscape of energy storage technologies (ESTs) in Saudi Arabia is emerging, with battery storage at the forefront. A notable example is the 1,300 MWh lithium-ion battery system for The Red Sea Project, contracted to Huawei in 2021, powering a 100% renewable tourism hub with solar energy [92]. Lithium-ion batteries dominate due to declining costs (~\$300/kWh in 2023) [93] and adaptability, though high temperatures (e.g., 33.6°C in Riyadh) necessitate cooling systems to maintain performance. Hydrogen storage is advancing through the \$8.4 billion NEOM Green Hydrogen Project, which will produce 600 tons of hydrogen daily by 2026 using 4 GW of renewables, reducing CO₂ emissions by 5 million tons annually. TES supports CSP, with the 50 MW Waad Al-Shamal plant using molten salt storage for 6–8 hours of nighttime power, though CSP contributes minimally (<0.1% of electricity) [94]. Pumped Hydro Storage (PHS) is virtually absent, despite a regional capacity of 4,365 MW across Arab countries, due to high costs (\$1,000–2,000/kW) and limited suitable sites. Smart grid initiatives, including 10 million smart meters planned by 2025, enhance storage integration by optimizing demand [95].

Despite progress, ESTs face significant challenges. For instance, high ambient temperatures and dust reduce battery lifespan, with lithium-ion systems losing 2–3% capacity annually without thermal management, increasing maintenance costs [96]. Batteries, hydrogen production (\$10–15/kg), and TES systems (\$50–100/kWh) remain relatively expensive compared to PV technologies [97]. PHS is constrained by geography and water scarcity, raising environmental concerns. Hydrogen storage requires extensive infrastructure for transport and utilization, limiting scalability beyond NEOM [98]. Policy gaps, such as undefined incentives for storage and reliance on imported technologies, elevate costs. Grid integration remains complex, as the Saudi Electricity Company (SEC) network, structured in four regional divisions, requires upgrades for bidirectional flows and variable renewable inputs. These hurdles underscore the need for tailored solutions to maximize EST adoption [99].

Looking ahead, Saudi Arabia can strengthen EST deployment through strategic measures. Investing in R&D for heat-resistant batteries, like solid-state or sodium-ion, could enhance durability in harsh climates. Exploring PHS along the Red Sea, integrated with desalination, could address water constraints while adding storage capacity, potentially saving 7 GW by 2030. Scaling hydrogen storage requires localized electrolyzer manufacturing and export infrastructure, leveraging PIF's \$10 billion commitment announced in 2024. Expanding TES with CSP projects, such as the 206 MW Al-Shuaibah plant by 2026, can ensure dispatchable power, with costs expected to drop 20% by 2030 [100]. Policy reforms, including tax incentives and mandates for storage in renewable projects, could accelerate uptake. Enhancing smart grids for rural microgrids in areas, like Tabuk, will improve access and resilience.

Economic Benefits of RE Development

The KSA may experience a 25% decrease in fossil fuel consumption in the water and energy sectors by 2030, as per the IRENA report [101]. This is due to the expansion of RE in Saudi Arabia, which is

delivering substantial economic benefits, aligning with the goals of Vision 2030 to diversify the economy, create jobs, and reduce reliance on oil revenues. In this regard, according to IRENA, RE projects in the Kingdom are expected to generate over 750, 000 jobs by 2030, both directly and indirectly. These include opportunities in construction, operations, and maintenance, R&D, and manufacturing, particularly for solar panels and wind turbine components. For instance, the Sakaka plant generated 1, 200 jobs during peak construction, while localized supply chains aim to boost employment in regions like Al Jouf and Rafha. Also, transitioning to renewables helps the Kingdom reduce subsidies for fossil-fuel-generated electricity. At present, the Saudi government subsidizes electricity charges in the KSA at nearly SAR 0.18/kWh. As of 2025, the average cost of solar PV electricity in the United States ranges between \$0.06 and \$0.08 per kWh [102].

In contrast, Saudi Arabia's Sakaka Solar PV Plant – the Kingdom's first utility-scale solar project – secured an investment of \$320 million and achieved a then-record low tariff of 0.08872 SAR/kWh (\$0.024/kWh). This highly competitive pricing underscores the potential of RE technologies to significantly lower electricity costs over time, especially when compared to conventional energy sources. In addition, according to Aziz et al. (2024) [103], the development of a green hydrogen economy could contribute \$20 billion to the national GDP by 2030, positioning Saudi Arabia as a major exporter in the global clean energy market. In this regard, the NEOM green hydrogen project is expected to produce around 650 tons of hydrogen per day, generate billions in export revenue, further diversify the economy, and enhance foreign direct investment, which reached 5.7% of GDP in 2023. Moreover, by 2030, replacing oil-fired power with renewables could save up to 500, 000 barrels of oil per day.

At an average oil price of \$80/barrel, this equates to \$14.6 billion annually in additional export revenue – a critical hedge against volatile oil markets. Renewables are projected to contribute \$12 billion annually to Saudi GDP and will help Saudi Arabia avoid 28 million tons of CO₂ emissions annually by 2030. While primarily environmental, this also mitigates future economic risks tied to carbon-intensive industries such as potential carbon taxes or trade barriers.

EMISSIONS AND ENVIRONMENTAL IMPACT IN KSA: CURRENT STATUS AND FUTURE DIRECTIONS

Saudi Arabia, a leading global energy producer, faces major environmental challenges from its heavy reliance on fossil fuels, which significantly contribute to GHG emissions. As the Kingdom advances its Vision 2030 goals for RE and sustainability, understanding its current emissions profile is essential. This section reviews the status of energy-related emissions, their sectoral distribution, and environmental impacts, and outlines future mitigation strategies and initiatives aligned with national and global climate targets.

Current Emissions Profile

Recently, Saudi Arabia's total CO₂ emissions from fuel combustion reached 532.875 million tons (Mt) CO₂, reflecting a 127% increase from 2000 levels (Figure 21), driven by rapid economic growth and energy demand. Per capita emissions recently increased in the KSA by around 34% compared to 2000, as shown in Figure 21 and reported by the IEA [104].

Also, per capita GHG emissions in Saudi Arabia are 2.6 times the G20 average, with a decrease of 3.7% between 2013 and 2018. Additionally, according to the climate transparency report [105], per capita emissions from the building sector are nearly double the G20 average, with direct and indirect emissions making up 0.95% and 16.60% of total energy-related CO₂ emissions, respectively.

The report also highlighted that Saudi Arabia emits 614.2 g of CO₂ for every kilowatt-hour of electricity. Total carbon dioxide emissions were 472, 186 gigagrams (Gg), methane emissions were 2, 067 Gg, and nitrous oxide emissions were 34.47 Gg, according to the 2010 GHG Inventory.

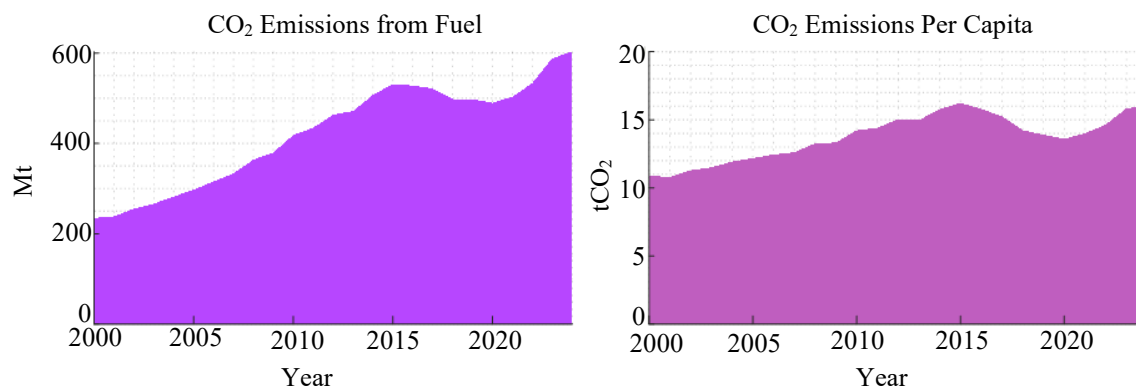


Figure 21. CO₂ emissions from fuel combustion and emissions per capita in the KSA.

Source: The figure is adopted based on data from [104].

Based on [106], the energy sector dominates emissions, with power generation alone accounting for 49% of total energy-related CO₂ emissions in 2022. Within power generation, oil, and natural gas were nearly equal contributors, emitting 130.165 Mt CO₂ and 129.859 Mt CO₂, respectively. This reliance on fossil fuels for electricity underscores the sector's environmental footprint, as depicted in Figure 22, which shows emissions trends since 2000, with a steady rise correlating with increased energy consumption.

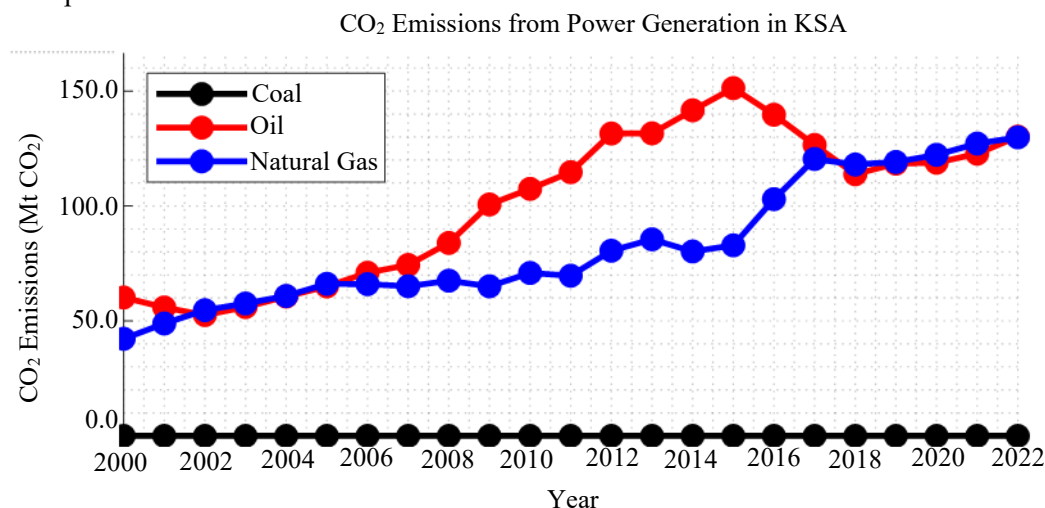


Figure 22. Emissions from power generation by source in Saudi Arabia since 2000.

Source: The figure is adopted based on data from [106].

Globally, Saudi Arabia contributed 1.6% of CO₂ emissions from combustible fuels in 2022, ranking it among significant emitters, though its per capita emissions remain high (Figure 21), reflecting an energy-intensive economy [107]. Figure 23 highlights Saudi Arabia as the second-largest CO₂ emitter in the Middle East, with emissions exceeding 500 Mt CO₂, following Iran. This high emission level reflects the country's heavy dependence on fossil fuels, particularly for electricity generation, transportation, and industrial activities.

Saudi Arabia's Nationally Determined Contribution (NDC) goal entails a notable surge of 416–562% from the levels recorded in 1990, equating to around 861–1,105 MtCO₂e by the year 2030. This target deviates from the prescribed 1.5°C temperature threshold, resulting in an ambition gap of 502 MtCO₂e. To stay within the 1.5°C limit, emissions would need to be around 359 MtCO₂e by 2030 – highlighting a significant challenge in aligning current trajectories with climate goals [105]. Compared to other regional countries, like the UAE, Iraq, and Kuwait, Saudi Arabia's emissions, are substantially higher, underscoring the urgent need for energy transition [107]. Sectoral analysis (Figure 24) reveals that

beyond power, transportation, and industry are major emitters, with oil refining and petrochemical production amplifying the carbon intensity of the industrial sector.

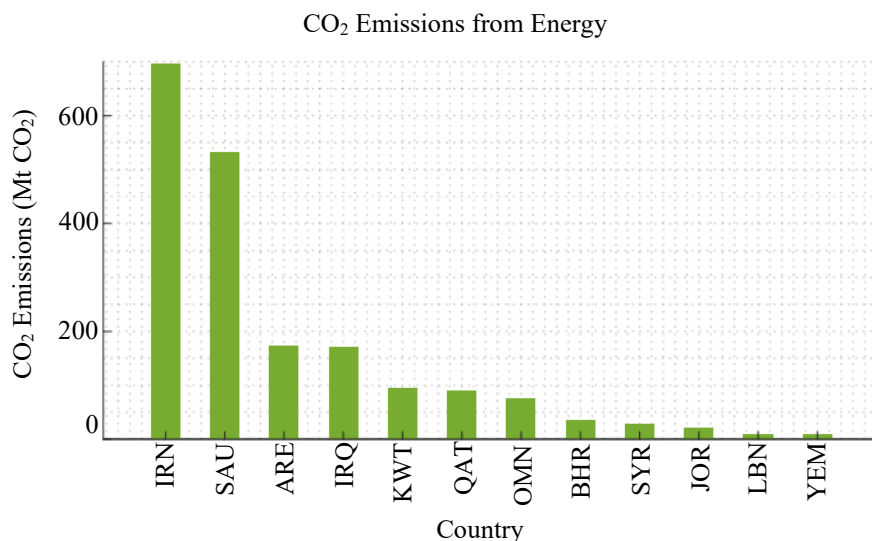


Figure 23. CO₂ emissions from energy sector, regional ranking.

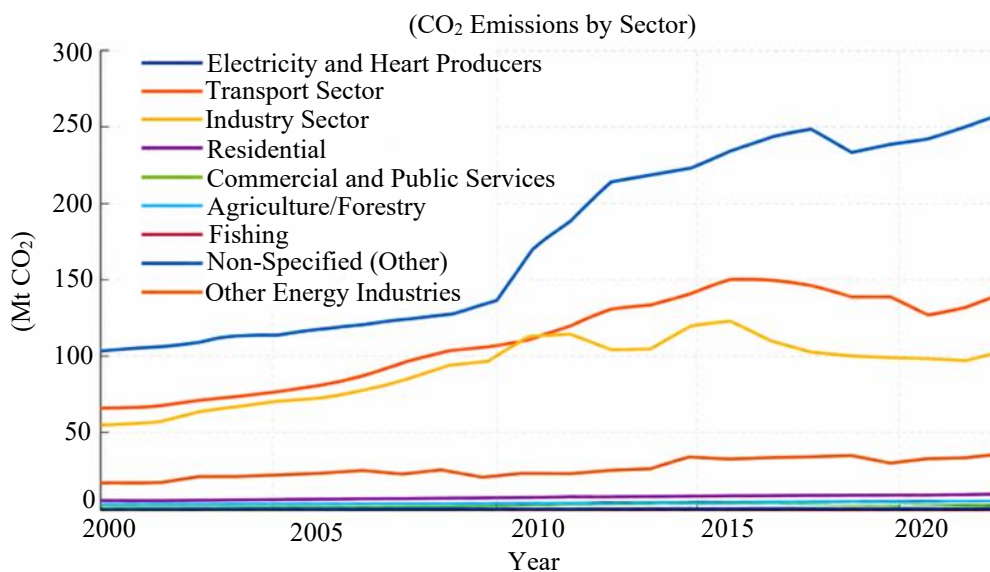


Figure 24. CO₂ emissions by sector in Saudi Arabia.

Source: The figure is based on data from [104].

Environmental Impacts

The environmental consequences of these emissions are profound, exacerbating climate change and local environmental degradation. High CO₂ emissions contribute to global warming, with Saudi Arabia experiencing rising average temperatures (e.g., 33.6°C in Riyadh annually) and increased frequency of extreme weather events, such as heatwaves and dust storms, impacting agriculture and water resources [108]. Air pollution from fossil fuel combustion, including particulate matter and sulfur oxides, poses health risks, with urban centers, like Riyadh and Dammam, reporting elevated levels of respiratory issues. Methane leaks from oil and gas operations, though not quantified in the provided data, further amplify greenhouse impacts [109]. Additionally, the energy sector's water-intensive processes strain Saudi Arabia's scarce freshwater resources, with desalination plants, often fossil-fueled, contributing to both emissions and marine ecosystem stress [110]. These impacts underscore the urgency of transitioning to cleaner energy systems to mitigate long-term environmental damage.

Current Mitigation Efforts

Saudi Arabia is making substantial progress toward its net-zero emissions target by 2060, driven by a series of strategic initiatives under Vision 2030 and the Saudi Green Initiative (SGI) [4, 5]. The Kingdom has committed to reducing 278 million tons of CO₂ annually by 2030 through a combination of RE deployment, carbon capture and storage (CCS), energy efficiency programs, and afforestation [4, 23]. Based on Al-Sinan et al. (2023) [111], major renewable projects, including the 2.6 GW Sudair Solar Plant and 1.5 GW Al-Shuaibah Solar Facility, are expected to significantly displace fossil fuel usage – Sudair alone reduces emissions by 2.9 Mt CO₂/year. The national goal is to meet 50% of electricity demand from renewables by 2030, scaling up from an installed capacity of 2.8 GW in 2023 – a 300% increase from 2022. Concurrently, Saudi Aramco aims to reach net-zero Scope 1 and 2 emissions by 2050 and is piloting CCS projects, like the one in Jubail Industrial City, designed to capture 9 Mt CO₂ annually by 2027. Hydrogen is also central to the strategy, with targets to produce 4 million tons of low-carbon hydrogen per year by 2030, including the \$8.4 billion NEOM Green Hydrogen Plant, which will produce 1.2 million tons of ammonia annually by 2026. The analysis in [71] posits that meeting 18% of Saudi Arabia’s total primary energy demand with hydrogen would require approximately 12 million tons of hydrogen annually by 2050. This projection is based on an assumed annual growth rate of 2.5% in total final energy consumption. As shown in Figure 25, this level of hydrogen adoption could result in a significant reduction in carbon emissions – estimated at around 440 million tons of CO₂ per year. A hybrid approach, incorporating multiple hydrogen production pathways, may offer a more cost-effective solution.

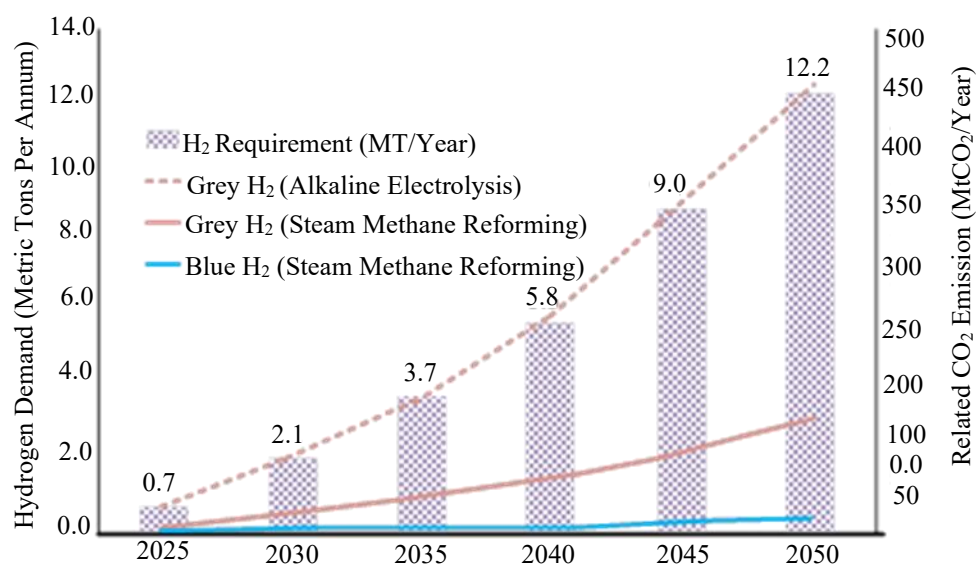


Figure 25. Evaluation of Saudi Arabia’s hydrogen integration and corresponding CO₂ emission mitigation.

Source: Adopted from [71].

The SGI also includes domestic planting of 10 billion trees, with 50 million already planted by 2023, while the Middle East Green Initiative, led by KSA, aims to plant 50 billion trees regionally and cut 670 million tons of CO₂ equivalent. In parallel, the Kingdom plans to install 10 million smart meters by 2025 and has already achieved 1.5 Mt CO₂ in emissions reduction through energy efficiency programs. In the power sector, according to CARE K (2012) [112], there are emissions reduction targets with a 60% reduction in CO₂ emissions, 75% in NO_x, and 70% in SO₂ emissions from power plants [112]. A summary of the main programs, initiatives, and their roles in emission reduction is listed in Table 9. These efforts are backed by \$10 billion in PIF sustainability investments and 15% methane emissions cut by 2030, positioning Saudi Arabia to lead a balanced and impactful transition toward a low-carbon future.

Table 9. The future role of different initiatives and projects in KSA emission reduction goals.

Ref.	Project/initiative	Role in emission reduction
[17, 23, 62].	Neom green hydrogen projects	–NEOM will host the world’s largest green hydrogen project, using 4 GW of renewables to produce 600 tons daily by 2026 – equivalent to 1.2 million tons of green ammonia annually – cutting 5 Mt CO ₂ each year. –Other projects aim for 2.9 Mt CO ₂ by 2030 and 4 Mt CO ₂ by 2035, using KSA’s solar and wind resources.
[4]	V2030	Saudi Arabia targets net-zero emissions by 2060. Under Vision 2030, it plans to cut 278 Mt CO _{2e} annually by 2030 and reach 50% RE, up from an earlier goal of 130 Mt.
[37]	SEEP	SEEP improves efficiency in buildings, industry, and transport, saving 0.4 million barrels of oil equivalent daily and reducing emissions by 15 Mt CO _{2e} yearly by 2030.
[23]	Saudi Aramco	Saudi Aramco targets net-zero Scope 1 and 2 emissions by 2050 and is piloting a CCS project in Jubail to capture 9 Mt CO ₂ annually by 2027.
[113]	National RE program	Aims for 58.7 GW of RE (solar/wind) by 2030, cutting 40+ million tons CO ₂ /year.
[113]	SEC	To address high emissions from electricity generation, Saudi Arabia has set ambitious targets: a 60% reduction in CO ₂ , 75% in NO _x , and 70% in SO ₂ from power plants.
[37]	ACWA Power	The CO ₂ intensity of gross electricity generation decreased in 2022–0.43 t CO ₂ /MWh for the total portfolio and 0.42 t CO ₂ /MWh for ACWA Power’s equity share.
[26]	Smart Grid	the Kingdom plans to install 10 million smart meters by 2025 and has already achieved 1.5 Mt CO ₂ in emissions reduction through energy efficiency programs.
[76]	Sudair Solar PV Plant	Generates 1.5 GW of solar power, cutting 2.9 Mt CO ₂ annually by replacing oil and gas in the national grid.
[51]	Amaala Solar Project	Expected to save 0.5 Mt CO ₂ annually by powering the Amaala tourism site with renewables, replacing fossil fuels-based power.
[114]	Red Sea Project	100% renewable-powered tourism; reduces 500,000 tons CO ₂ /year via solar and green hydrogen.
[105, 115]	Saudi CCE	Framework to reduce, reuse, and remove emissions; aligns with Saudi Net-Zero 2060 goal
[116, 117]	Jubail CCS Hub	Captures and stores 9 million tons of CO ₂ annually starting in 2027, aiming for 44 million tons by 2035, reducing emissions from industries like oil refining and petrochemicals.
[114]	Middle East Green Initiativ	Regional effort to eliminate 670 million tons CO ₂ via tree planting and cross-border cooperation.
[25]	Saudi (PIF) Green Investments	Invests \$10 billion in renewables and sustainability projects to decarbonize key sectors.
[118]	Riyadh Metro	Offers electric public transport for 3.6 million passengers yearly, cutting transport emissions by about 0.3 million tons of CO _{2e} through reduced private vehicle use.
[114]	Saudi Arabia’s Mangrove Initiative	Plans to plant 100 million mangroves by 2030, sequestering 2.5 million tons CO ₂ annually.
[77]	Sakaka PV Plant	300 MW solar plant offsetting 430,000 tons CO ₂ /year by replacing fossil-fueled generation.
[18, 119]	Saudi Arabia’s Blue Hydrogen Project	Aramco’s blue hydrogen (from natural gas + CCUS) targets 11 million tons CO ₂ /year capture.
[5]	Green Riyadh Initiative	Planting 7.5 million trees to reduce urban heat and absorb 3.5 million tons CO ₂ by 2030.
[120]	building retrofit program (TARSHID)	Adding 38 GW of rooftop PV capacity could produce 51 TWh/year and avoid 29 Mt of CO ₂ emissions.
[56]	Dumat Al Jandal Wind Farm	400 MW wind farm reducing 988,000 tons CO ₂ /year; Saudi Arabia’s first utility-scale wind project.
[37]	Saudi Arabia’s EV Infrastructure Plan	Targets 30% EV penetration by 2030; cuts transport emissions by 9 million tons CO ₂ /yea
[114]	Riyadh Waste-to-Energy Program	Diverts 94% of Riyadh’s waste from landfills, composting 1.3 million tons of biodegradable waste to cut 4.1 million tons of CO _{2e} annually through methane avoidance and energy recovery.

Saudi Arabia’s Nationally Determined Contribution (NDC) is centered on the CCE approach (Figure 26), which builds on the circular economy concept but focuses specifically on energy and GHG emissions rather than material flows.

The CCE is structured around four key actions – Reduce, Reuse, Recycle, and Remove. It aims to reduce emissions through improved energy and process efficiency, electrification, RE, and low-carbon fuels. Reuse involves utilizing captured carbon without chemical alteration for applications such as enhanced oil recovery, fuel, and feedstock production.

Recycling converts CO₂ and GHGs into new products through chemical processes, including fuels and polymers. Finally, removal addresses residual emissions through CO₂ removal technologies and nature-based solutions that capture and store CO₂ already in the atmosphere.

While Saudi Arabia’s net-zero GHG emissions strategy by 2060 emphasizes a shift to RE, carbon dioxide removal (CDR) measures will also be essential.

The continued role of hydrocarbons in hard-to-decarbonize sectors means residual emissions will persist, requiring CDR technologies to offset their impact [121]. According to the analysis conducted by Kamboj et al. (2024) [23].

Saudi Arabia must implement CDR measures to extract 371 MtCO₂ annually from the atmosphere by 2060 to offset total GHG emissions and achieve net-zero targets (Figure 27). It is important to note that sectors, such as shipping, aviation, heavy transport, and various industrial activities, are currently considered difficult to decarbonize due to existing technological and research limitations.

Nevertheless, the potential for comprehensive decarbonization in these sectors remains promising, given ongoing technological advancements.

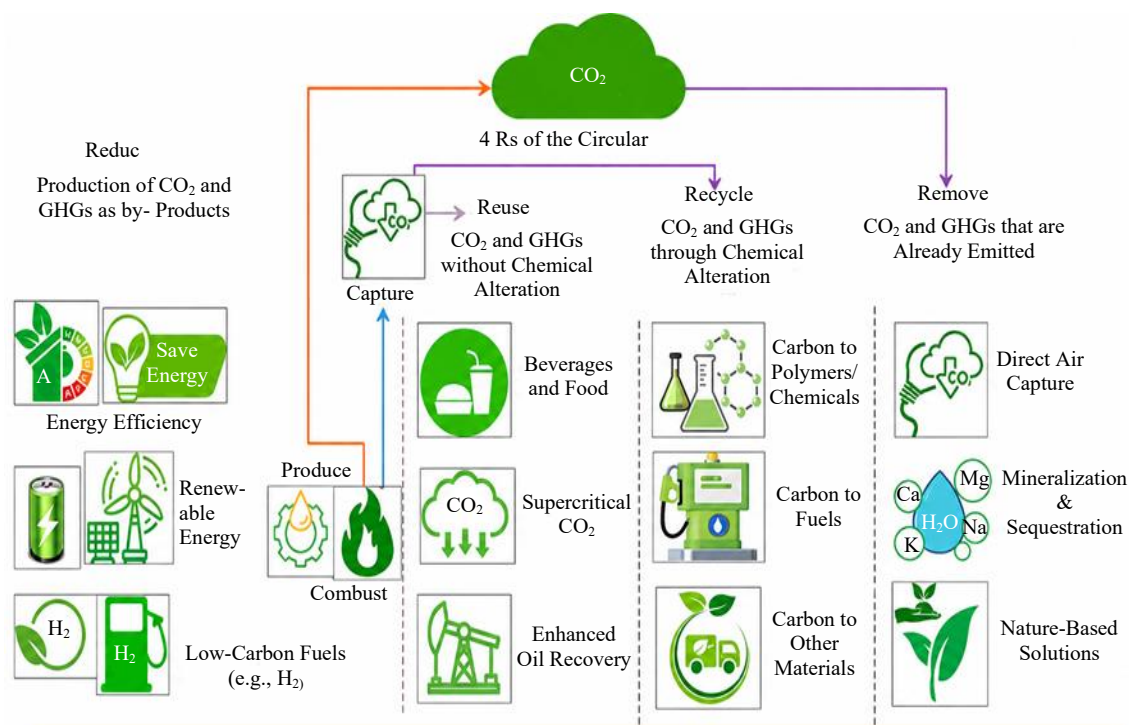


Figure 26. Circular carbon economy 4Rs.

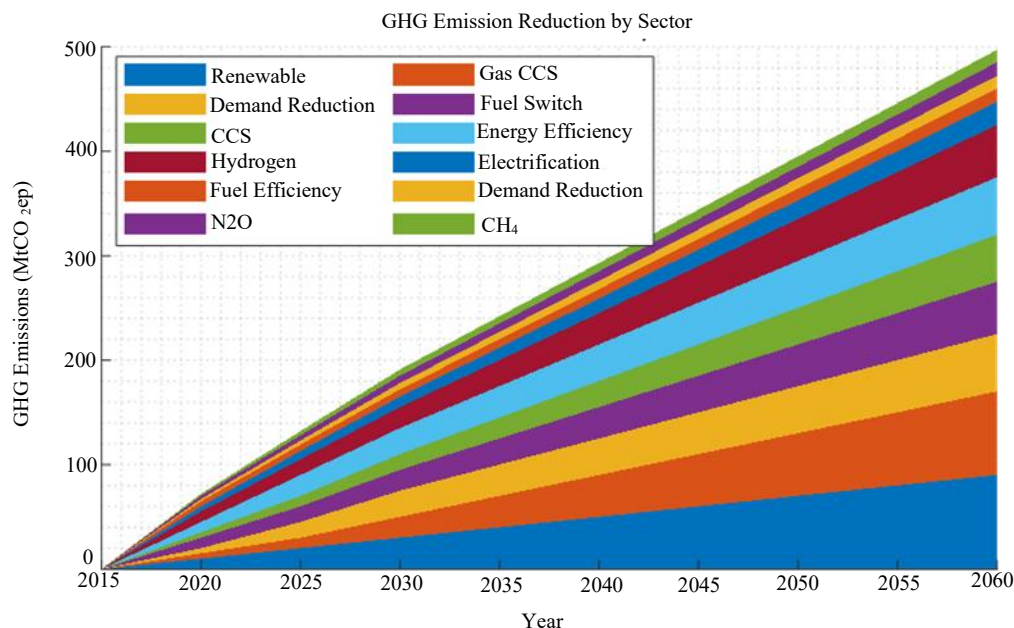


Figure 27. Expected emission reduction by sector 2015–2060 [23].

POLICIES, CHALLENGES, AND FUTURE DIRECTIONS OF SUSTAINABLE TRANSITION IN KSA

The KSA has embarked on a transformative journey to diversify its economy and reduce its reliance on fossil fuels through sustainable energy and environmental initiatives. This section examines the policies driving this transition, identifies persistent challenges, and outlines future directions to achieve long-term sustainability goals.

Policies and Regulatory Frameworks

To draw global investors, ensure economic sustainability, and combat climate change, developing sustainable infrastructure and enforcing clear standards is vital. The current energy regulations emphasize the importance of licensing, installation guidelines, and measures for safety, efficiency, and consumer protection in the RE sector [122]. Additionally, emphasis was placed on enforcing tendering procedures for RE projects and adjusting electricity pricing. According to Iqbals et al. (2019) [123], structural reforms and policy adjustments are key to enhancing energy efficiency, lowering CO₂ emissions, and aligning economic practices with environmental sustainability. A comprehensive review of the regulatory framework should also consider the challenges arising from global oil price volatility and large-scale RE integration [124]. Specialized agencies are essential for advancing the RE transition. Key among these are reliable data providers and regulatory bodies like the RE Project Development Office (REPDO) and the King Abdullah City for Atomic Renewable Energy (KACARE) [125]. These operate alongside power sector reforms aimed at promoting privatization, competition, and energy efficiency. Additionally, the Electricity & Co-generation Regulatory Authority (ECRA) [126] plays a vital role in developing regulations for self-consumed RE and coordinating efforts among organizations involved in renewable initiatives. Recently, KSA's sustainable transition is underpinned by strategic policy frameworks, most notably Saudi Vision 2030, which prioritizes environmental sustainability and RE deployment [4, 127]. Also, the V2030 and its subsidiary Saudi Green Initiative (SGI) aim to reduce carbon emissions by 278 million tons annually by 2030 and achieve net-zero by 2060 [111, 128]. Central to this is the NREP, targeting 50% RE in the power mix by 2030 [37]. The Carbon Circular Economy (CCE) Framework prioritizes carbon capture, utilization, and storage (CCUS), alongside green hydrogen production, positioning KSA as a future exporter of clean energy. This framework promotes emissions management through the (4R) reduction, reuse, recycling, and removal [109, 128]. The National Energy Services Company (Tarshid), fully owned by the Public Investment Fund (PIF), was established in 2017 with the aim of leading the national energy services sector. Its mission aligns

with a key pillar of Saudi Vision 2030 – sustainability – by promoting energy efficiency and supporting the development of a circular carbon economy in the Kingdom [42]. Regulatory reforms have catalyzed privatization, with entities like ACWA Power leading renewable investments [77]. The Saudi Energy Efficiency Program (SEEP) enforces standards for appliances and industries, while the National Environment Strategy addresses biodiversity and land degradation [37, 129]. Internationally, KSA has joined the Global Methane Pledge and invested in cross-border initiatives, like the Middle East Green Initiative [5], aiming to plant 50 billion trees regionally and partnerships with international organizations, like the IRENA, further bolster these efforts [51]. However, the lack of a comprehensive energy policy framework hinders coordinated implementation, as sectoral policies remain fragmented and require further attention to attain the ambitious Saudi transition goals.

Challenges

The KSA has made strong progress toward aligning its energy and environmental goals with global sustainability efforts. However, its transition to RE and climate change mitigation faces complex challenges that must be addressed to achieve its sustainable targets. The main challenges are summarized as follows:

Economic and Structural Dependencies

KSA's economy remains heavily reliant on fossil fuels, with oil and gas accounting for approximately 50% of GDP and 70% of export earnings. This dependency creates a paradox: while oil revenues fund RE projects (e.g., the 500 billion NEOM megaproject), the transition risks destabilizing the primary revenue stream that underpins national budgets [4, 62, 130]. Phasing out fossil fuel subsidies – estimated at 30–40 billion annually – poses political and economic risks, as cheap energy prices are entrenched in societal expectations [130]. Technological and financial barriers also impede progress, with RE and storage technologies requiring substantial investment – e.g., lithium-ion batteries cost \$139/kWh in 2024 [131], and hydrogen production ranges from \$10–15/kg [132]. Transitioning to renewables requires overcoming entrenched economic interests, infrastructure tailored to oil and gas, and a workforce skilled predominantly in hydrocarbon industries. The high initial costs of RE projects, such as solar and wind farms, coupled with the need for advanced energy storage systems to address intermittency, pose financial and technical hurdles in a region with abundant, low-cost oil [133]. Also, subsidized fossil fuel prices reduce the financial incentive for RE adoption. Despite the introduction of some reforms, the complete removal of subsidies still poses political and social challenges [124]. Additionally, attracting private investment in renewables requires competitive returns, which are challenged by high upfront capital costs for solar, wind, and green hydrogen infrastructure compared to well-established hydrocarbon technologies.

Technological and Infrastructural Gaps

Despite its abundant solar and wind resources, Saudi Arabia faces significant technological and infrastructural challenges in scaling up RE deployment. The intermittent nature of solar and wind power requires advanced energy storage solutions – such as grid-scale batteries and hydrogen storage – which are still in the early stages of development [134, 135]. Environmental conditions pose additional challenges. The Kingdom's harsh climate – including extreme heat, frequent dust storms, and high humidity – negatively impacts the performance and longevity of solar panels. High temperatures reduce photovoltaic efficiency, while dust accumulation hinders output and increases the need for regular cleaning, which is particularly demanding in a water-scarce environment [135, 136]. Moreover, the current energy grid infrastructure is not fully equipped to handle the variability of RE sources. Integrating large shares of renewables into the national grid necessitates significant upgrades to transmission systems and the adoption of smart grid technologies [26]. However, these modernization efforts are still developing and lag behind international best practices. The lack of technical expertise and readiness in smart grid implementation further complicates integration [26, 137]. Additionally, while solar energy is abundant, its efficiency is limited by environmental stressors. Wind energy, though promising, is geographically constrained to specific sites, limiting its widespread applicability [138].

Water–Energy Nexus

The interdependence between water and energy presents a significant challenge for RE deployment in Saudi Arabia, where water is a scarce resource [139]. Many renewable technologies, particularly those involving hydrogen production and cooling systems, require substantial water input. PV systems, for instance, need regular cleaning to maintain efficiency, which increases water demand – especially problematic in arid regions [140]. Additionally, the production of green hydrogen depends on desalinated water, a process that is both energy-intensive and currently reliant on fossil fuels, potentially offsetting the environmental benefits of renewable hydrogen [15, 141]. Balancing water consumption with RE expansion and broader sustainability goals is essential. As the kingdom pursues large-scale renewable projects, integrating water-efficient technologies and transitioning to renewable-powered desalination will be critical to addressing this nexus sustainably.

Institutional and Regulatory Hurdles

While Vision 2030 outlines a clear strategic direction for energy transition, institutional fragmentation and bureaucratic inertia continue to hinder implementation. The involvement of multiple stakeholders – including the Ministry of Energy, Saudi Aramco, and the Public Investment Fund (PIF) – has led to overlapping responsibilities and coordination challenges [43, 142, 143]. These complexities can delay decision-making and reduce the efficiency of project execution. The regulatory landscape for RE in Saudi Arabia remains in a state of transition. Gaps in policy coordination, regulatory clarity, and standardization can hinder the implementation of large-scale renewable projects and reduce investor confidence [43]. Furthermore, key frameworks related to RE auctions, land allocation, grid access, and carbon pricing are still evolving, creating uncertainty that may deter potential investors [144]. Saudi Arabia aspires to lead in hydrogen production, but the global hydrogen industry still lacks clear policies, safety standards, and international regulations needed for its growth [145]. Inconsistent policies and lack of standardization further complicate the deployment of large-scale renewable projects. Another critical barrier is the shortage of a skilled domestic workforce in RE technologies. Although programs, such as the National Industrial Development and Logistics Program (NIDLP), seek to localize clean energy industries, progress in building technical capacity has been slow [37]. Strengthening vocational training, enhancing STEM education, and fostering industry–academia collaboration are essential to developing the expertise needed to design, operate, and maintain RE systems. To accelerate the adoption of RE, Saudi Arabia must prioritize institutional coordination, regulatory clarity, and workforce development to create a more stable and investor-friendly environment.

Social and Cultural Factors

Public awareness of climate change and energy conservation remains limited, partly a result of long-standing fossil fuel subsidies, which have contributed to a culture of high energy consumption and low cost-awareness [75]. Encouraging a societal shift toward sustainability requires comprehensive public education campaigns, incentive programs, and community-based initiatives aimed at promoting energy efficiency and environmental responsibility. Thus, a cultural transformation is essential to fostering long-term behavioral change and public support for RE policies. Land-use conflicts also present a social challenge [146]. Large-scale RE projects – such as the 1.5 GW Sudair Solar Plant – often overlap with traditional agricultural or tribal lands, highlighting the need for early and transparent stakeholder engagement to mitigate disputes and ensure inclusive development [147]. A recent study [148] found that while most Saudi respondents were moderately informed about RE, challenges persist. For example, 79.2% of participants expressed concern about pollution and recognized the potential benefits of alternative energy sources. However, 97.2% believed that the high costs associated with renewable technologies hinder their effectiveness and accessibility. To accelerate adoption, it is crucial to address public perceptions, enhance energy literacy, and involve local communities in the planning and implementation of RE initiatives.

Geopolitical and Environmental Trade-offs

As the world’s largest oil exporter, Saudi Arabia faces a complex balancing act between advancing its climate commitments and maintaining its strategic geopolitical and economic influence [149].

Efforts to reduce fossil fuel production and align with global decarbonization targets may create diplomatic and economic challenges, particularly with energy-importing nations that rely on stable oil supplies [150]. On the domestic front, the rapid expansion of RE infrastructure carries environmental implications. Large-scale solar and wind projects often require vast land areas, which can encroach upon ecologically sensitive regions – such as desert ecosystems – that are critical for biodiversity and environmental balance [135, 136, 151]. Without careful planning and environmental assessments, RE development may inadvertently threaten the very ecosystems it seeks to protect. Addressing these trade-offs requires integrated policies that align climate action with national interests, international relations, and environmental sustainability.

Climate-Specific Vulnerabilities

Ironically, climate change exacerbates challenges in RE deployment. Rising temperatures reduce solar panel efficiency by 10–25%, while frequent sandstorms damage equipment and increase operational costs [111]. Meanwhile, achieving carbon neutrality requires addressing emissions from hard-to-abate sectors, like cement, steel, and aviation, where scalable low-carbon technologies (e.g., carbon capture, utilization, and storage) are not yet commercially viable [128, 152].

Future Directions and Recommendations

Based on the literature review and the discussions presented in this study, several key future directions are proposed to advance RE development and climate change mitigation in Saudi Arabia.

Scaling Up Renewable Energy Capacity

To accelerate the energy transition, Saudi Arabia must continue expanding its renewable energy capacity by leveraging its vast solar and wind resources. With abundant sunlight and expansive desert landscapes, the Kingdom is prioritizing large-scale deployment of solar PV and CSP technologies. Projects, such as the Sakaka and Sudair solar plants, and the 400 MW Dumat Al Jandal Wind Farm – the largest in the Middle East – highlight significant progress. Future strategies should emphasize expanding RE generation across high-resource regions including Al-Jouf, Tabuk, and the Red Sea coast [43]. Offshore and onshore wind developments, particularly in the Red Sea and the Persian Gulf, will help diversify the energy mix and reduce reliance on conventional sources [153]. Aiming to generate 50% of its electricity from renewable sources by 2030, Saudi Arabia must also focus on streamlining project financing, promoting local manufacturing of RE components, and enhancing smart grid infrastructure to manage variable energy supply. Moreover, flagship projects, like NEOM's Helios Green Hydrogen Plant Position Saudi Arabia as a future global exporter of green hydrogen, capitalizing on its solar advantage. Furthermore, expanding renewable portfolios to include geothermal and waste-to-energy is important to diversify the mix. To ensure the reliability of RE, investments in grid-scale energy storage systems, such as advanced batteries and pumped hydro storage, will be essential to address intermittency and stabilize supply.

Enhancing Energy Efficiency

Enhancing energy efficiency is a critical component of Saudi Arabia's climate strategy, especially given its historically high per capita energy consumption. The Saudi Energy Efficiency center (SEEC) is leading efforts to improve energy use across all major sectors [52]. In the built environment, enforcing stricter energy codes for new constructions and retrofitting existing buildings with efficient technologies – such as improved insulation, HVAC systems, and lighting – will significantly reduce energy demand. In industries that use a lot of energy, like petrochemicals, using new technologies like carbon capture, utilization, and storage (CCUS), along with digital tools for monitoring and optimizing energy use, will enhance energy efficiency and cut down emissions. The transport sector also presents significant opportunities for improvement through the promotion of electric vehicles (EVs), the expansion of EV charging infrastructure, and investment in public transportation systems to reduce dependency on fossil-fuel-powered vehicles. Looking ahead, scaling up demand-side management (DSM) programs and providing incentives for energy-efficient appliances through subsidies and rebates will be essential to minimizing energy waste. These efforts, combined with public awareness campaigns and behavioral change initiatives, will play a vital role in achieving national energy efficiency and climate goals.

Advancing Carbon Capture and Storage (CCS)

Advancing CCS is central to Saudi Arabia's strategy for reducing emissions from its oil, gas, and industrial sectors. The Kingdom is making significant investments in CCS technologies, exemplified by Saudi Aramco's Hawiyah Gas Plant CCS project, which captures up to 800,000 tons of CO₂ annually – making it one of the largest initiatives of its kind in the region [154]. Looking ahead, future projects should aim to scale CCS infrastructure across key industrial hubs and integrate it with blue hydrogen production to support the decarbonization of fossil fuel-based industries. In addition to storage, utilizing captured carbon for enhanced oil recovery (EOR), the production of synthetic fuels, or other industrial applications presents opportunities to extract economic value from CCS technologies. Moreover, integrating circular economy principles into industrial and urban planning – through waste-to-energy systems and CCUS infrastructure – can reduce emissions and resource waste. To accelerate large-scale deployment, Saudi Arabia must prioritize the development of a comprehensive regulatory framework for carbon storage, alongside fostering international partnerships to exchange knowledge, technical expertise, and best practices in CCS implementation.

Strengthening Policy and International Cooperation

Strengthening policy frameworks and enhancing international cooperation are essential for Saudi Arabia to achieve its net-zero emissions target by 2060, as committed in its Nationally Determined Contributions (NDCs) under the Paris Agreement. Central to this effort is the promotion of the Circular Carbon Economy (CCE) framework, which focuses on reducing, reusing, recycling, and removing carbon emissions – offering a comprehensive approach to shaping future climate policies [68]. Saudi Arabia is actively engaging in global environmental initiatives, such as the Green Middle East Initiative [114], and is playing a key role in hosting COP29-related discussions, signaling its intent to align national strategies with international climate goals. Regionally, strengthening regional collaborations, such as interconnected Gulf Cooperation Council (GCC) smart grids, would optimize RE sharing and stability [155]. Also, strengthening regional interconnections for energy sharing and establishing a circular economy regulatory framework will enhance resource efficiency. Moreover, policy enhancements must include carbon pricing mechanisms, green bonds, and public–private partnerships to attract investment. It is important to introduce tax breaks for renewables, a carbon trading scheme, and stricter emissions regulations to drive private sector alignment. Domestically, the expansion of financial incentives for RE projects, the introduction of carbon pricing mechanisms, and the enforcement of stricter emissions regulations will be critical in stimulating private-sector investment and innovation. Energy efficiency initiatives should be a central focus of energy policy frameworks, including demand-side management measures and pricing reforms. A promising area for further research involves exploring financial arrangements between consumers and service providers for energy exchange, especially in the context of rooftop solar PV systems. Moving forward, aligning national policies with global standards and fostering robust public–private partnerships will be vital in enhancing the effectiveness, credibility, and long-term success of the Kingdom's climate initiatives.

Investing in Research, Innovation, and Workforce Development

To sustain its RE transition and long-term climate goals, Saudi Arabia should focus on research, innovation, and human capital development. The establishment of dedicated R&D centers is crucial in fostering the development of next-generation renewable technologies, advanced energy storage systems, and climate resilience strategies tailored to regional conditions. From a research perspective, focus group discussions offer an effective method for examining the challenges and opportunities of decarbonizing the oil and gas sector through direct engagement with industry stakeholders. They can reveal key barriers, policy gaps, and collaboration pathways for emission reduction. Progress in this area also depends on strong internal commitment and clear strategies to reduce subsidy consumption – an essential element of the broader energy transition. Equally important is the expansion of vocational training and academic programs aimed at building a skilled workforce proficient in RE, energy efficiency, and environmental technologies. Moreover, human capital development, expanding vocational training in renewables will build local expertise. Public campaigns to promote energy conservation and community engagement in RE projects, like NEOM, can foster societal buy-in. In

parallel, the Kingdom should embrace digital transformation by integrating artificial intelligence (AI), the Internet of Things (IoT), and big data analytics to optimize energy systems, energy demand forecasting, emissions monitoring, forecasting climate risks, and improving resource management. Looking ahead, fostering innovation ecosystems through startup incubators, research-industry partnerships, and international collaboration will be instrumental in positioning Saudi Arabia as a regional and global hub for green technology and sustainable innovation.

Investing in Research, Innovation, and Workforce Development

In addition to mitigation efforts, it is important that Saudi Arabia increasingly prioritize climate adaptation to address the growing impacts of rising temperatures, water scarcity, and desertification. A key focus is on enhancing water management through investments in renewable-powered desalination plants and the adoption of advanced water recycling technologies to secure sustainable water supplies. In the agricultural sector, the Kingdom should promote climate-smart practices, including the use of drip irrigation systems and drought-resistant crops, to overcome the lack of water resources. Looking ahead, the development of early warning systems for extreme weather events and the integration of climate risk assessments into urban planning and infrastructure development will be essential to enhancing national resilience and ensuring long-term sustainability.

CONCLUSION

Saudi Arabia stands at a critical crossroads in its national development pathway, where the imperatives of economic diversification, environmental sustainability, and global climate commitments converge. This review has comprehensively examined the Kingdom's energy transition trajectory, highlighting the ambitious scope of Vision 2030, the Saudi Green Initiative (SGI), and the National Renewable Energy Program (NREP), which collectively seek to transform a hydrocarbon-dependent economy into a resilient, innovation-driven, low-carbon future. Central to this vision is the targeted deployment of 58.7 GW of RE by 2030 – comprising solar, wind, and concentrated solar power – complemented by pioneering initiatives such as the NEOM Green Hydrogen Project and large-scale carbon capture and storage (CCS) operations. While the review recognizes substantial progress in RE deployment, institutional reforms, and global engagement, it also identifies persistent and multi-layered challenges. Chief among these are economic dependencies on oil revenues (accounting for over 50% of GDP), extensive energy subsidies (~\$35 billion/year), fragmented governance among key stakeholders, and underdeveloped regulatory frameworks. Technical constraints – including solar efficiency degradation due to dust and heat, limited grid flexibility, and the water-energy nexus – further complicate the integration of renewables and green hydrogen technologies. Socio-cultural resistance and limited public awareness of sustainable practices add to the complexity, underscoring the need for behavioral change alongside infrastructural and technological development. This review underscores the critical need for a holistic energy strategy that integrates technological innovation, regulatory reform, and socio-economic adaptation. While substantial progress has been made, gaps remain in grid modernization, policy frameworks, and public engagement – challenges that are compounded by annual energy subsidies exceeding \$35 billion, infrastructural limitations, and socio-cultural resistance. Moreover, emissions from power generation and industry, which account for nearly half of the country's carbon output (49% of CO₂), require urgent attention. To overcome these obstacles, Saudi Arabia must invest in advanced energy storage, resilient technologies for extreme climates, and effective carbon capture solutions. Institutional coordination, a robust R&D ecosystem, and cross-sectoral collaboration will be essential to modernize governance structures and foster innovation. This paper highlights the economic and strategic value of RE – not only in reducing emissions and creating jobs, but also in supporting GDP diversification and strengthening energy security. By synthesizing the technical, economic, and socio-political dimensions of its energy transition, Saudi Arabia has the potential to position itself as a global leader in sustainable energy. Achieving this vision will depend on fostering inclusive policies, enhancing technological readiness, and aligning national efforts with global sustainability agendas.

The review highlights that Saudi Arabia's transition is not solely a technical endeavor but a profound socio-economic and institutional transformation. The challenges identified demand systemic, integrated solutions that align national priorities with global sustainability agendas such as the Paris Agreement and the UN Sustainable Development Goals (SDGs). The findings emphasize the urgency of the following strategic priorities:

- Accelerate investments in RE infrastructure, scale adoption, smart grids, microgrids, energy storage systems, sodium-ion, pumped hydro, and hydrogen storage systems to manage renewable intermittency and enhance grid stability.
- Advance the circular carbon economy (CCE) by strengthening the deployment of CCS/CCUS technologies, especially in hard-to-abate sectors. Also, expand carbon capture infrastructure – such as the Jubail Hub, which targets 9 MtCO₂ per year – and integrate it with blue hydrogen production to support the decarbonization of the oil, gas, and industrial sectors.
- Embed the 4Rs – reduce, reuse, recycle, remove – in policy and industrial planning to optimize carbon flows and resource use.
- Gradually reduce \$35 billion/year subsidies while incentivizing renewable adoption through tax breaks, green bonds, and carbon pricing mechanisms.
- Strengthen policy coherence and institutional coordination across ministries and agencies to streamline mandates and implementation.
- Foster international partnerships to enhance financing, technology transfer, and R&D collaboration – particularly in developing heat-resilient and water-efficient technologies. Prioritize investments in R&D for heat-resistant solar panels, dust mitigation systems, and AI-driven energy management to address climate-specific challenges such as extreme heat and sandstorms.
- Develop a local skilled renewable-energy workforce via expanded vocational training and industry-academia fellowships to build domestic expertise in project development, operation, and maintenance of solar, wind, hydrogen, and CCS systems.
- Develop key policies such as fossil fuel subsidy phase-out, carbon pricing, energy efficiency standards, CCUS, water-energy nexus management, green finance, and electric mobility. Establish an auditor (e.g., Saudi Climate Commission) to assess effectiveness and enforce compliance, supported by robust monitoring and evaluation frameworks.
- Promote energy efficiency across sectors by enforcing strict building codes, retrofitting existing infrastructure, expanding demand-side management (DSM), and expanding electric vehicle (EV) networks to reduce per capita energy consumption.
- Develop key policies such as fossil fuel subsidy phase-out, carbon pricing, energy efficiency standards, CCUS, water-energy nexus management, green finance, and electric mobility. Establish an auditor (e.g., Saudi Climate Commission) to assess effectiveness and enforce compliance, supported by robust monitoring and evaluation frameworks.
- Promote energy efficiency across sectors by enforcing strict building codes, retrofitting existing infrastructure, expanding demand-side management (DSM), and expanding electric vehicle (EV) networks to reduce per capita energy consumption.
- Create investor-friendly policies (e.g., standardized auctions, land allocation frameworks) to attract capital for large-scale solar, wind, and hydrogen projects.
- Promote renewable-powered desalination and hydrogen production, addressing both energy security and water scarcity.
- Launch comprehensive education and incentive programs to shift cultural attitudes – enhancing awareness of energy conservation, renewables' benefits, and the costs of carbon-intensive choices.

Ultimately, Saudi Arabia's ability to harmonize its hydrocarbon legacy with RE innovation will determine its role as a global leader in climate action and sustainable development. By leveraging its natural resources, strategic vision, and growing institutional momentum, the Kingdom can offer a replicable model for other resource-rich nations navigating similar transitions. This review underscores the critical importance of interdisciplinary research, multi-stakeholder cooperation, and sustained

political will to achieve a just and resilient transition to a low-carbon future. The stakes are not only national but global, positioning Saudi Arabia as a potential pioneer in shaping the energy landscape of the post-carbon era.

Disclosure Statement

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.

Author Contributions

CRediT: Ali Q. Alshetwi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Funding

Not applicable.

Data Availability Statement

All data supporting the findings of this study are presented within the article.

REFERENCES

1. Al-Shetwi AQ, Abidin IZ, Mahafzah KA, Hannan MJ. Feasibility of future transition to 100% renewable energy: Recent progress, policies, challenges, and perspectives. *J Clean Prod.* 2024;478:143942.
2. International Renewable Energy Agency (IRENA). *Renewable Capacity Highlights 2025*. Abu Dhabi: IRENA; 2025.
3. International Energy Agency (IEA). *Renewables 2023: Analysis and forecasts to 2028* [Internet]. 2024 [cited 2026 May 22]. Available from: <https://www.iea.org/reports/renewables-2023>
4. Saudi Vision 2030. *Saudi Vision 2030: A Story of Transformation* [Internet]. 2025 Jan 2 [cited 2026 May 22]. Available from: <https://www.vision2030.gov.sa/en>
5. Saudi Green Initiative. *Saudi Arabia is taking a multidimensional approach to emissions reduction* [Internet]. 2025 Jan 3 [cited 2026 May 22]. Available from: <https://www.sgi.gov.sa/about-sgi/sgi-targets/reduce-carbon-emissions/>
6. Belaid F, Al-Sarihi A. Saudi Arabia energy transition in a post-Paris agreement era: An analysis with a multi-level perspective approach. *Res Int Bus Finance.* 2024;67:102086.
7. Salam MA, Khan SA. Transition towards sustainable energy production—A review of the progress for solar energy in Saudi Arabia. *Energy Explor Exploit.* 2018;36(1):3–27.
8. Zubair MJ. PV energy penetration in Saudi Arabia: Current status, residential, and commercial users, local investment, use in modern agriculture. *Int J Sustain Eng.* 2024;17(1):39–51.
9. Almasoud A, Gandayh HM. Future of solar energy in Saudi Arabia. *J King Saud Univ Eng Sci.* 2015;27(2):153–157.
10. AlGhamdi SA, Abdel-Latif AM, Abd El-Kawi OS, Abouelatta OB. Analysis of wind speed data and wind energy potential for seven selected locations in KSA. *J Power Energy Eng.* 2022;10(4):1–26.
11. Imam AA, Abusorrah A, Marzband M. Potentials and opportunities of solar PV and wind energy sources in Saudi Arabia: Land suitability, techno-socio-economic feasibility, and future variability. *Results Eng.* 2024;21:101785.
12. Suliman FEM. Solar- and wind-energy utilization in the Kingdom of Saudi Arabia: A comprehensive review. *Energies.* 2024;17(8):1894.
13. Aldubyan M, Gasim A. Energy price reform in Saudi Arabia: Modeling the economic and environmental impacts and understanding the demand response. *Energy Policy.* 2021;148:111941.
14. Al-Shetwi AQ, Atawi IE, Abuelrub A, Hannan M. Techno-economic assessment and optimal design of hybrid power generation-based renewable energy systems. *Technol Soc.* 2023;75:102352.

15. Aziz G, Sarwar S, Khan MS, Waheed R, et al. The prospect of green hydrogen in Saudi Arabia: An overview of theoretical and empirical approach. *Environ Sci Pollut Res*. 2024;31(5):6597–6609.
16. Boretti A. Green hydrogen electrolyzer and hydrogen-methane CCGT power plant in NEOM City. *Int J Hydrogen Energy*. 2024;67:1056–1064.
17. Wouters F. Green Hydrogen in Saudi Arabia’s NEOM. In: *The Clean Hydrogen Economy and Saudi Arabia*. Routledge; 2024. p.98–111.
18. Al-Khelaiwi MS, Al-Masaabi TA, Farag H, Rehman SJ, et al. Evaluation of green and blue hydrogen production potential in Saudi Arabia. *Energy Convers Manag X*. 2024;24:100742.
19. Al Harbi F, Csala D. Saudi Arabia’s electricity: Energy supply and demand future challenges. In: *2019 1st Global Power, Energy and Communication Conference (GPECOM)*. IEEE; 2019. p.467–472.
20. Amran YA, Amran YM, Alyousef R, Alabduljabbar H. Renewable and sustainable energy production in Saudi Arabia according to Saudi Vision 2030; Current status and future prospects. *J Clean Prod*. 2020;247:119602.
21. Al-Douri Y, Waheeb S, Voon CJ. Review of the renewable energy outlook in Saudi Arabia. *J Renew Sustain Energy*. 2019;11(1).
22. Barhoumi E, et al. Renewable energy resources and workforce case study Saudi Arabia: Review and recommendations. *J Therm Anal Calorim*. 2020;141:221–230.
23. Kamboj P, Hejazi M, Qiu Y, Kyle P, Iyer G. The path to 2060: Saudi Arabia’s long-term pathway for GHG emission reduction. *Energy Strateg Rev*. 2024;55:101537.
24. Mir MA, Chang SK. Saudi Arabia E-waste management strategies, challenges and opportunities, effect on health and environment: A strategic review. *Emerg Contam*. 2024:100357.
25. Public Investment Fund (PIF). PIF Program 2021-2025 [Internet]. 2021 Jan 4 [cited 2026 May 22]. Available from: <https://www.pif.gov.sa/en/strategy-and-impact/the-program/>
26. Khan KA, Quamar MM, Al-Qahtani FH, Asif M, Alqahtani M, Khalid M. Smart grid infrastructure and renewable energy deployment: A conceptual review of Saudi Arabia. *Energy Strateg Rev*. 2023;50:101247.
27. Al-Homoud MS, Krarti M. Energy efficiency of residential buildings in the Kingdom of Saudi Arabia: Review of status and future roadmap. *J Build Eng*. 2021;36:102143.
28. Amran YA, Amran YM, Alyousef R, Alabduljabbar H. Renewable and sustainable energy production in Saudi Arabia according to Saudi Vision 2030; Current status and future prospects. *J Clean Prod*. 2020;247:119602.
29. Selim MM, Alshareef N. Trends and opportunities in renewable energy investment in Saudi Arabia: Insights for achieving Vision 2030 and enhancing environmental sustainability. *Alex Eng J*. 2025;112:224–234.
30. Alnatheer O. The potential contribution of renewable energy to electricity supply in Saudi Arabia. *Energy Policy*. 2005;33(18):2298–2312.
31. Hassan Q, Sameen AZ, Salman HM, Jaszczur M, Al-Hitmi M, Alghoul M. Energy futures and green hydrogen production: Is Saudi Arabia trend? *Results Eng*. 2023;18:101165.
32. Mezghani I, Haddad HB. Energy consumption and economic growth: An empirical study of the electricity consumption in Saudi Arabia. *Renew Sustain Energy Rev*. 2017;75:145–156.
33. AlNemer HA, Hkiri B, Tissaoui K. Dynamic impact of renewable and non-renewable energy consumption on CO2 emission and economic growth in Saudi Arabia: Fresh evidence from wavelet coherence analysis. *Renew Energy*. 2023;209:340–356.
34. Aziz G, Sarwar S, Nawaz K, Waheed R, Khan MS. Influence of tech-industry, natural resources, renewable energy and urbanization towards environment footprints: A fresh evidence of Saudi Arabia. *Resour Policy*. 2023;83:103553.
35. AlGhamdi A. Saudi Arabia energy report. *King Abdullah Pet Stud Res Cen*. 2020;19:1–28.
36. Bahgat G. Will Saudi Arabia face an energy crisis? *J Soc Polit Econ Stud*. 2012;37(2):181.
37. Islam MT, Ali A. Sustainable green energy transition in Saudi Arabia: Characterizing policy framework, interrelations and future research directions. *Next Energy*. 2024;5:100161.

38. Ibrahiem DM, Hanafy SA, Esily RR. Appraising the role of energy subsidy on the environmental sustainability in Arab Nations-is it compatible or confronting? *Int J Glob Warm*. 2024;32(1):65–80.
39. Rahman SM, et al. Electricity generation in Saudi Arabia: Tracing opportunities and challenges to reducing greenhouse gas emissions. *IEEE Access*. 2021;9:116163–116182.
40. Al-Saidi M. Energy transition in Saudi Arabia: Giant leap or necessary adjustment for a large carbon economy? *Energy Rep*. 2022;8:312–318.
41. Kamboj P, Hejazi M, Qiu Y, Kyle P, Iyer G. Saudi Arabia Net-Zero GHG Emissions by 2060: Transformation of the Transport Sector. 2024.
42. Tarshid. A Thriving Energy Efficiency [Internet]. 2017 Mar 1 [cited 2026 May 22]. Available from: <https://www.tarshid.com.sa/en/about-us>
43. Al-Gahtani SF. Saudi Arabia's journey toward a renewable future. *Energies*. 2024;17(11):2444.
44. Gasim AA, Matar W. Revisiting energy subsidy calculations: A focus on Saudi Arabia. *Energy J*. 2023;44(1):245–276.
45. International Energy Agency (IEA). Energy system of Saudi Arabia [Internet]. 2023 Mar 18 [cited 2026 May 22]. Available from: <https://www.iea.org/countries/saudi-arabia>
46. Saudi Electricity Company. Statistics and Sustainability [Internet]. 2025 Mar 23 [cited 2026 May 22]. Available from: <https://www.se.com.sa/Sustainability>
47. Al-Shetwi AQ. Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges. *Sci Total Environ*. 2022;822:153645.
48. Fahmy MSE, Ahmed F, Durani F, Bojnec Š, Ghareeb MM. Predicting electricity consumption in the Kingdom of Saudi Arabia. *Energies*. 2023;16(1):506.
49. International Energy Agency (IEA). Total electricity production, Middle East [Internet]. 2025 Feb 25 [cited 2026 May 22]. Available from: <https://www.iea.org/regions/middle-east/electricity>
50. Derouez F, et al. Energy, technology, and economic growth in Saudi Arabia: An ARDL and VECM analysis approach. *Heliyon*. 2024;10(4).
51. International Energy Agency (IEA). Energy system of Saudi Arabia [Internet]. 2024 Mar 5 [cited 2026 May 22]. Available from: <https://www.iea.org/countries/saudi-arabia>
52. Saudi Energy Efficiency Center (SEEC). Efficiency for a better future, more sustainable resources [Internet]. 2017 Mar 24 [cited 2026 May 22]. Available from: <https://www.seec.gov.sa/en>
53. Belaïd F, Massié C. The viability of energy efficiency in facilitating Saudi Arabia's journey toward net-zero emissions. *Energy Econ*. 2023;124:106765.
54. Alaqeel T, Suryanarayanan S. A comprehensive cost-benefit analysis of the penetration of Smart Grid technologies in the Saudi Arabian electricity infrastructure. *Utilities Policy*. 2019;60:100933.
55. Alhaidari N, Elshurafa A, Felder F. Achieving Renewable Energy Targets Without Compromising the Power Sector's Reliability. 2021.
56. Almutairi K, Alahmadi R. The feasibility of the first utility-scale wind farm in Saudi Arabia (the 400 MW Dumat Al-Jandal Project). *J Clean Energy Technol*. 2022;10(1):1–10.
57. Manal A. The Role of Renewable Energy in Driving Economic Transformation and Sustainable Development in Saudi Arabia. *Int J Energy Econ Policy*. 2025;15(1):364–373.
58. R Consultancy. Saudi Arabia's \$270 Billion Green Energy Leap: A Golden Opportunity for Businesses [Internet]. 2024 Feb 2 [cited 2026 May 22]. Available from: <https://www.linkedin.com/pulse/saudi-arabias-270-billion-green-energy-leap-golden-opportunity-j5v6f/>
59. Public Investment Fund (PIF). Giga-Projects [Internet]. 2022 Mar 23 [cited 2026 May 22]. Available from: <https://www.pif.gov.sa/en/our-investments/giga-projects/>
60. Bader EH, et al. The Heart of Innovation in SPARK, Saudi Arabia. *Concr Int*. 2023;45(6).
61. NEOM Green Hydrogen Company (NGHC). Building The World's Largest Green Hydrogen Plant [Internet]. 2024 Feb 10 [cited 2026 May 22]. Available from: <https://nghc.com/>
62. NEOM. NEOM Green Hydrogen Company completes financial close [Internet]. 2023 Mar 13 [cited 2026 May 22]. Available from: <https://www.neom.com/en-us/newsroom/neom-green-hydrogen-investment>
63. Abdelkawy NA, Al Shammre A, Aljohar MZ. Insights into Saudi Arabia's economic transformation: Renewable energy, FDI, and GDP dynamics. *J Econ Stud*. 2024.

64. Albalawi AA, Nezamuddin N, Felder FA, Muhsen A, Elshurafa A. Assessment of the Potential of Floating Offshore Wind Turbines in the Red Sea. King Abdullah Petroleum Studies and Research Center; 2024.
65. Mukhtarov S, Azizov M, Kartal MT, Eynalov H. Catalyzing green transformation: Mitigating oil price impact on CO₂ emissions in Saudi Arabia via renewable energy transition. *Environ Econ Policy Stud.* 2024;1–23.
66. Zhang J, Li J. Revolution in renewables: Integration of green hydrogen for a sustainable future. *Energies.* 2024;17(16):4148.
67. Raza A, Mahmoud M, Arif M, Alafnan SJ. Underground hydrogen storage prospects in the Kingdom of Saudi Arabia. *Fuel.* 2024;357:129665.
68. Saxena S, Braun JF, Shabaneh R, Roychoudhury J. The clean hydrogen economy and Saudi Arabia: Findings and final thoughts. In: *The Clean Hydrogen Economy and Saudi Arabia.* Routledge; 2024. p.713–750.
69. Aljohani Z, Asiri A, Al-Awlaqi S, Aljohani T, AbdelMeguid H. Assessment of solar energy availability and its potential applications in NEOM region. *Renew Energy Res Appl.* 2024;5(1):11–19.
70. Saif AGH, Alquaity AB, Mokheimer EM. Techno-economic analysis of green hydrogen production in Saudi Arabia: A comparative study of solar PV and CSP technologies. *Int J Hydrogen Energy.* 2025;105:1361–1374.
71. Hasan S, Shabaneh R. The economics and resource potential of hydrogen production in Saudi Arabia. 2021.
72. Sadiq M, Alshehhi RJ, Urs RR, Mayyas A. Techno-Economic Analysis of Green H₂@ Scale in Saudi Arabia. SSRN. 2023.
73. KAPSARC. Saudi Arabia Bets Big On Blue Hydrogen [Internet]. 2022 [cited 2026 May 22]. Available from: <https://www.kapsarc.org/news/saudi-arabia-bets-big-on-blue-hydrogen/>
74. Farahat A, Kambezidis HD, Labban A. The Solar Radiation Climate of Saudi Arabia. *Climate.* 2023;11(4):75.
75. Mosly I, Makki AA. Current status and willingness to adopt renewable energy technologies in Saudi Arabia. *Sustainability.* 2018;10(11):4269.
76. Ali A. Transforming Saudi Arabia’s energy landscape towards a sustainable future: Progress of solar photovoltaic energy deployment. *Sustainability.* 2023;15(10):8420.
77. ACWA Power. Driving the transition to a cleaner, greener future [Internet]. 2023 Feb 16 [cited 2026 May 22]. Available from: <https://www.acwapower.com/en/>
78. U.S.-Saudi Business Council. Water in Saudi Arabia: Desalination, wastewater, and privatization. 2021.
79. Al-Hanoot AK, Mokhlis H, Mekhilef S, Alghoul M, Shareef H, Samatar AM. Distributed PV systems in Saudi Arabia: Current status, challenges, and prospects. *Energy Strateg Rev.* 2024;55:101535.
80. Chen W, Castruccio S, Genton MG, Crippa P. Current and future estimates of wind energy potential over Saudi Arabia. *J Geophys Res Atmos.* 2018;123(12):6443–6459.
81. Rehman S, Baseer M, Alhems L. GIS-based multi-criteria wind farm site selection methodology. *FME Trans.* 2020;48(4):855–867.
82. Global Wind. Global Wind Atlas–Saudi Arabia [Internet]. 2025 Apr 2 [cited 2026 May 22]. Available from: <https://globalwindatlas.info/en/area/Saudi%20Arabia>
83. Ferroukhi R, et al. Renewable energy market analysis—The GCC region. Abu Dhabi: International Renewable Energy Agency; 2016.
84. Naqash MT, Aburamadan MH, Harireche O, AlKassem A, Farooq QU. The potential of wind energy and design implications on wind farms in Saudi Arabia. *Int J Renew Energy Dev.* 2021;10(4):839.
85. Demirbas A. A Realistic Fuel Alternative for Diesel Engines. 2007.
86. Demirbas A, Alidrisi H, Ahmad W, Sheikh MH. Potential of geothermal energy in the Kingdom of Saudi Arabia. *Energy Sources A Recovery Util Environ Eff.* 2016;38(15):2238–2243.
87. Hussein MT, Lashin A, Al Bassam A, Al Arifi N, Al Zahrani I. Geothermal power potential at the western coastal part of Saudi Arabia. *Renew Sustain Energy Rev.* 2013;26:668–684.

88. Daiem MMA, Said N. Energetic, economic, and environmental perspectives of power generation from residual biomass in Saudi Arabia. *Alex Eng J.* 2022;61(5):3351–3364.
89. Elhassan RM. Potential Opportunities for Waste to Energy and Recycling in the Kingdom of Saudi Arabia. In: 2021 6th International Conference on Renewable Energy: Generation and Applications (ICREGA). IEEE; 2021. p.76–81.
90. Saudi Energy Consulting. Record-Breaking Energy Storage: Saudi Arabia Leads with 12.5GWh Project [Internet]. 2025 Apr 13 [cited 2026 May 22]. Available from: <https://saudienergyconsulting.com/>
91. Hamdan A, Daudu CD, Fabuyide A, Etukudoh EA, Sonko S. Next-generation batteries and US energy storage: A comprehensive review: Scrutinizing advancements in battery technology, their role in renewable energy, and grid stability. *World J Adv Res Rev.* 2024;21(1):1984–1998.
92. Alhakbani A. Battery Blueprint: Saudi Arabia’s Strategic Foray into the Battery Value Chain. Massachusetts Institute of Technology; 2024.
93. Deorah SM, Abhyankar N, Arora S, Gambhir A, Phadke A. Estimating the cost of grid-scale lithium-ion battery storage in India. LBNL report; 2020.
94. Q Energy. Saudi Arabia energy needs and nuclear power. 2018.
95. Hasan AA, Hanieh AA, Juaidi A. Energy storage: Status and future perspective in Arab countries. *Energy Storage.* 2024;6(1):e550.
96. Caldera U, Breyer C. The role that battery and water storage play in Saudi Arabia’s transition to an integrated 100% renewable energy power system. *J Energy Storage.* 2018;17:299–310.
97. International Renewable Energy Agency (IRENA). Renewable capacity highlights [Internet]. 2023 Mar 20 [cited 2026 May 22]. Available from: <https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/>
98. Boretti A. Assessing the value of hydrogen thermal energy storage and electric thermal energy storage in NEOM city. *Int J Hydrogen Energy.* 2024;49:1133–1147.
99. Boretti A. The perspective of enhanced geothermal energy integration with concentrated solar power and thermal energy storage. *Energy Storage.* 2022;4(1):e303.
100. Nassar AK. Strategic energy transition in the Gulf Cooperation Council: Balancing economic, social, political, and environmental dynamics for sustainable development. *Int J Green Energy.* 2024:1–17.
101. IRENA. Renewable Energy Outlook for ASEAN: Towards a Regional Energy Transition. 2nd ed. International Renewable Energy Agency; 2020.
102. Wang Y, et al. Global spatiotemporal optimization of photovoltaic and wind power to achieve the Paris Agreement targets. *Nat Commun.* 2025;16(1):2127.
103. Aziz G, Sarwar S, Khan MS, Waheed R. The prospect of green hydrogen in Saudi Arabia: an overview of theoretical and empirical approach. *Environ Sci Pollut Res.* 2024;31(5):6597–6609.
104. IEA. How much CO2 does Saudi Arabia emit? What are the main sources of CO2 emissions in Saudi Arabia? 2024 Apr 1. Available from: <https://www.iea.org/countries/saudi-arabia/emissions>
105. Climate Transparency. Comparing G20 climate action towards net zero. 2021 Mar 13. Available from: <https://www.climate-transparency.org/wp-content/uploads/2021/10/CT2021SaudiArabia.pdf>
106. Osman Y. Implications of energy consumption by sector on carbon emissions in Saudi Arabia. *Int J Energy Econ Policy.* 2024;14(2):311–318.
107. Kouyakhhi NR. CO2 emissions in the Middle East: Decoupling and decomposition analysis of carbon emissions, and projection of its future trajectory. *Sci Total Environ.* 2022;845:157182.
108. Altouma A, et al. An environmental impact assessment of Saudi Arabia’s vision 2030 for sustainable urban development: A policy perspective on greenhouse gas emissions. *Environ Sustain Indic.* 2024;21:100323.
109. Shehri TA, Braun JF, Howarth N, Lanza A, Luomi MJ. Saudi Arabia’s climate change policy and the circular carbon economy approach. *Clim Policy.* 2023;23(2):151–167.
110. Alodah A. Towards sustainable water resources management considering climate change in the case of Saudi Arabia. *Sustainability.* 2023;15(20):14674.
111. Al-Sinan MA, Bubshait AA, Alamri F. Saudi Arabia’s journey toward net-zero emissions: Progress and challenges. *Energies.* 2023;16(2):978.
112. CARE K. Building the Renewable Energy Sector in Saudi Arabia. 2012.
113. Ministry of Energy. Sustainable Development. 2025. Available from: <https://www.moenergy.gov.sa/>

114. Saudi Green Initiative. SGI Initiatives. 2024 Mar 14. Available from: <https://www.sgi.gov.sa>
115. Braun JF. Saudi Arabia's Net-Zero World Narrative. 2024.
116. Rowaihy F, et al. Decarbonizing Saudi Arabia Energy and Industrial Sectors: Assessment of Carbon Capture Cost. *Carbon Capture Sci Technol*. 2025;14:100375.
117. Darraj N, Abdelrahman MM, Alklhi MY. Regional review for large-scale deployment of carbon capture and storage (CCS) in the Middle East. In: *Mediterranean Offshore Conference*; 2024. p. D021S020R001.
118. Anwar AM, Oakil AT, Muhsen A, Arora A. What would it take for the people of Riyadh city to shift from their cars to the proposed metro? *Case Stud Transp Policy*. 2023;12:101008.
119. Schoonover M, Alkhabbaz M, D'Agostini M. Saudi Arabia and the hydrogen economy: Blue and green hydrogen value chain. In: *The Clean Hydrogen Economy and Saudi Arabia*. Routledge; 2024. p. 500–517.
120. Almohammadi K, Allouhi A. Techno-economic assessment and optimization of grid-connected solar PV systems in Saudi Arabia's building sector. *Util Policy*. 2025;93:101885.
121. Qiu Y, Iyer G, Fuhrman J, Hejazi M, Kamboj P, Kyle P. The role and deployment timing of direct air capture in Saudi Arabia's net-zero transition. *Environ Res Lett*. 2024;19(6):064042.
122. Amiri AA, Wahid MN, Al-Buraiki AS, Al-Sharafi A. A strategic multi-criteria decision-making framework for renewable energy source selection in Saudi Arabia using AHP-TOPSIS. *Renew Energy*. 2024;236:121523.
123. Iqbal W, Altalbe A, Fatima A, Ali A, Hou Y. A DEA approach for assessing the energy, environmental and economic performance of top 20 industrial countries. *Processes*. 2019;7(12):902.
124. Blazquez J, Hunt LC, Manzano B. Oil subsidies and renewable energy in Saudi Arabia: A general equilibrium approach. *Energy J*. 2017;38(1 Suppl):29–46.
125. Kanybek K. Analytical Centres of the Kingdom of Saudi Arabia. *Russ Muslim World*. 2023;4(322):91–99.
126. Electricity and Co-Generation Regulatory Authority. *Co-Generation Regulatory Authority of Saudi Arabia Report*. 2018.
127. AlArjani A, Modibbo UM, Ali I, Sarkar BJ. A new framework for the sustainable development goals of Saudi Arabia. *J King Saud Univ Sci*. 2021;33(6):101477.
128. Matar W, Mansouri NY, Umeozor E. Energy policy pathways to inform climate policy in Saudi Arabia. *J Clean Prod*. 2024;445:141190.
129. Al-Tamimi NJ. A state-of-the-art review of the sustainability and energy efficiency of buildings in Saudi Arabia. *Energy Effic*. 2017;10(5):1129–1141.
130. Sfakianakis J. *The Economy of Saudi Arabia in the 21st Century: Prospects and Realities*. Oxford: Oxford University Press; 2024.
131. Orangi S, Manjong N, Clos DP, Usai L, Burheim OS, Strømman AH. Historical and prospective lithium-ion battery cost trajectories from a bottom-up production modeling perspective. *J Energy Storage*. 2024;76:109800.
132. Rubio-Garcia J, Kucernak A, Parra-Puerto A, Liu R, Chakrabarti BJ. Hydrogen/functionalized benzoquinone for a high-performance regenerative fuel cell as a potential large-scale energy storage platform. *J Mater Chem A*. 2020;8(7):3933–3941.
133. Özer S, Ersoy G. *Energy Transitions in the Middle East. The Middle East, Conflicts, and Wars*. 2024:341.
134. Alshahrani A. *Flexibility measures and energy management strategies for large-scale PV integration into grid system: a case study for Saudi Arabia [thesis]*. University of Nottingham; 2022.
135. Hassan Q, et al. Implement and evaluate resilient energy infrastructures capable of withstanding spatial, temporal, and annual weather fluctuations in Saudi Arabia by 2050. *Sustain Futures*. 2024;7:100182.
136. Abuzaid H, Awad M, Shamayleh AJ. Impact of dust accumulation on photovoltaic panels: A review paper. *Int J Sustain Eng*. 2022;15(1):264–285.
137. Düşteğör D, Sultana N, Felemban N, Al Qahtani DJ. A smarter electricity grid for the Eastern Province of Saudi Arabia: Perceptions and policy implications. *Util Policy*. 2018;50:26–39.

138. Alanazi A, Hassan I, Jan ST, Alanazi MJ, Policy E. Multi-criteria analysis of renewable energy technologies performance in diverse geographical locations of Saudi Arabia. *Clean Technol Environ Policy*. 2024;26(4):1165–1196.
139. Rambo KA, Warsinger DM, Shanbhogue SJ, Ghoniem AF. Water-energy nexus in Saudi Arabia. *Energy Procedia*. 2017;105:3837–3843.
140. Riera JA, Lima RM, Hoteit I, Knio OJ. Simulated co-optimization of renewable energy and desalination systems in Neom, Saudi Arabia. *Nat Commun*. 2022;13(1):3514.
141. Mustafa J, Alqaed S, Almehmadi FA, Malekshah EH, Sharifpur M. Effect of economic and environmental parameters on multi-generation of electricity, water, heat, and hydrogen in Saudi Arabia: A case study. *Int J Hydrogen Energy*. 2024;52:585–598.
142. Moshashai D, Leber AM, Savage JD. Saudi Arabia plans for its economic future: Vision 2030, the National Transformation Plan and Saudi fiscal reform. *Br J Middle East Stud*. 2020;47(3):381–401.
143. Hammad FB. The vision 2030: Corporate governance perspective in Saudi Arabia. *J Syst Manag Sci*. 2019;9(1):48–68.
144. Hajimineh R, Moghani AM. The important factors of Saudi Arabian policy-making in renewable energy resources. *Future Energy*. 2023;2(2):29–38.
145. Islam A, et al. Accelerating the green hydrogen revolution: A comprehensive analysis of technological advancements and policy interventions. *Int J Hydrogen Energy*. 2024;67:458–486.
146. Makki AA, Mosly I. Factors affecting public willingness to adopt renewable energy technologies: An exploratory analysis. *Sustainability*. 2020;12(3):845.
147. Alzahrary A, Kabir G, Al Zohbi G. Evaluation of the barriers to and drivers of the implementation of solar energy in Saudi Arabia. *Int J Sustain Dev World Ecol*. 2022;29(6):543–558.
148. Almulhim AI. Understanding public awareness and attitudes toward renewable energy resources in Saudi Arabia. *Renew Energy*. 2022;192:572–582.
149. Quamar MM. Saudi Arabia's Climate Change Policy: An Effort towards a Sustainable Future for the Kingdom and the Middle East. In: *BRICS and Climate Change: Balancing National Interests, National Development Goals and Global Environmental Sustainability*. Springer; 2024. p. 183–202.
150. Benlaria A, Sadaoui N, Almawishir NFS, Benlaria H. Navigating the oil-environment nexus: Saudi Arabia's challenge in sustainable development. *Int J Energy Econ Policy*. 2024;14(5):292–300.
151. McClung MR, Moran MD. Minimizing impacts of future renewable energy development on the world's desert ecosystems. *Front Sustain*. 2022;3:900468.
152. Kumar A, Tiwari AK, Milani DJ. Decarbonizing hard-to-abate heavy industries: Current status and pathways towards net-zero future. *Process Saf Environ Prot*. 2024.
153. Kiriakidis P, Christoudias T, Kushta J, Lelieveld J. Projected wind and solar energy potential in the eastern Mediterranean and Middle East in 2050. *Sci Total Environ*. 2024;927:172120.
154. Omri A, Euch J, Hasaballah AH, Al-Tit A. Determinants of environmental sustainability: Evidence from Saudi Arabia. *Sci Total Environ*. 2019;657:1592–1601.
155. Almasri RA, Narayan S. A recent review of energy efficiency and renewable energy in the Gulf Cooperation Council (GCC) region. *Int J Green Energy*. 2021;18(14):1441–1468.