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Recent Initiatives and Current Status of Clean and Sustainable Energy Adoption in the Kingdom of Saudi Arabia

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Abstract

The transition to clean and sustainable energy is critical for addressing Kingdom of Saudi Arabia (KSA)'s energy security challenges and reducing negative impacts on the environment. Reducing oil dependency, one of the primary goals of Vision 2030, the KSA set out to achieve in 2016. This study investigates the recent initiatives and the current status of clean energy adoption in KSA by identifying the key accomplishments and ongoing efforts to promote sustainability goals. The analysis includes the impact of the government's regulatory policies, planned investments, technological advancements, and sustainable transition. To achieve Vision 2030's target of generating 50% of its electricity from renewable sources, KSA is implementing key projects, including the 300 megawatts (MW) Sakaka Solar Plant, the 400 MW Dumat Al Jandal Wind Farm, and the groundbreaking $8.4 billion NEOM Green Hydrogen initiative, which aims to produce 650 tons of green hydrogen per day. Moreover, the KSA is modernizing its energy infrastructure through the installation of 10 million smart meters and upgrading decentralized smart grid technologies. Moreover, the review highlights asset benchmarking, lessons learned, challenges faced, and future pathways for clean energy adoption.

Keywords: Renewable energy transition; Solar energy; Wind energy; Energy policy and regulation; Sustainable development.
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1. Introduction

Energy is the lifeline of an economy, and a country self-reliant in the energy sector can guarantee its sovereignty, integrity, and security. However, fossil fuels (coal, gas, and oil) are not evenly distributed across countries, and their reserves do not regenerate once depleted; consequently, they have been steadily approaching exhaustion due to consistent consumption. Another key reason for the shift to Renewable energy (RE) is that energy produced using fossil fuels is not clean; hazardous gases and particles are produced as byproducts, which have been damaging the ozone layer that shields the earth from harmful rays.

RE techniques include solar, wind, hydropower, and geothermal energy. These sources rely on natural cycles, where their primary energy is filled automatically after a certain duration or through the recurrence of climate cycles. These techniques are efficient, cost-effective, and scalable, making them leading alternatives to conventional energy-producing techniques.

The Kingdom of Saudi Arabia (KSA), located in West Asia, is the largest country on the Arabian Peninsula, with a land area of about 2149690 sq. km (occupying 80% of the landmass).[1] Most of its terrain consists of arid desert (north and central Saudi Arabia), lowlands, steppe, and mountains (south and southwestern region).[2] The country is blessed with large reserves of fossil fuels. According to the latest studies and data collected by internationally recognized organizations (Worldometer), KSA holds 267 billion barrels of proven reserves of crude oil, the 2nd largest in the world, accounting for 16.2% of the world's total proven oil reserves. KSA ranks 6th in the world for oil consumption, accounting for 3.4% of the world's total consumption per day (97,103,871 barrels per day).[3] This consumption includes electricity generation, transportation, and heating or air-conditioning.

Fig. 1 illustrates the transition from fossil fuel-based emissions to clean energy adoption and the resulting benefits, such as lower CO_2 emissions, better air quality and long-term

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sustainability, each represented by a hexagon-shaped block.

In addition to long-hours sunlight, KSA occupies regional suitability of wind farm sites as identified by.[4] Based upon historical wind data, four potential regions have been highlighted. The Central region has the largest suitable area (8576 km^2) due to favorable wind resources and infrastructure connectivity.[4]

KSA's East Coast, along the Red Sea has high offshore wind energy potential, helping the Kingdom meet its Vision 2030 goal of generating 9.5 Gigawatts (GW) of RE.[5] Offshore wind is preferred over onshore wind because it has less intermittent, less turbulent, higher wind speeds and a lower environmental impact. The wind speed profile (average speed from 3 m/s to 7 m/s at a height of 10 m from the sea level) along the KSA's Red Sea coast is shown in Fig. 2. These areas have minimal limitations, have no nearby oil extraction facilities, and are strategically located to improve grid connectivity.[5]

KSA, blessed with one-fifth of the world's total oil reserves, is the leading exporter of oil. Massive industrialization, strategic partnership projects, and sole reliance on conventional energy production shift the focus to RE resources. Exploring innovative and sustainable energy solutions to meet its growing demands while maintaining its leadership role sets a trend for discovering new paradigms. KSA has enormous solar potential,[6] making it an ideal location for solar panel installations. For instance,[7] evaluates the feasibility parameters of grid-connected solar PV in the northern region of KSA, particularly in Dammam and Tabuk, to be favorable. Regulatory agencies, energy bodies, and the private sector vow to contribute to cleaner energy for total production and consumption.

Sustainable Development Goal (SDG) 7, clean and sustainable energy for all, has received special attention from all over the world, and all leading economies of the world have declared their manifestos to shift their energy/economy/industry progressively towards clean and sustainable energy.[8] Massive installation of solar energy

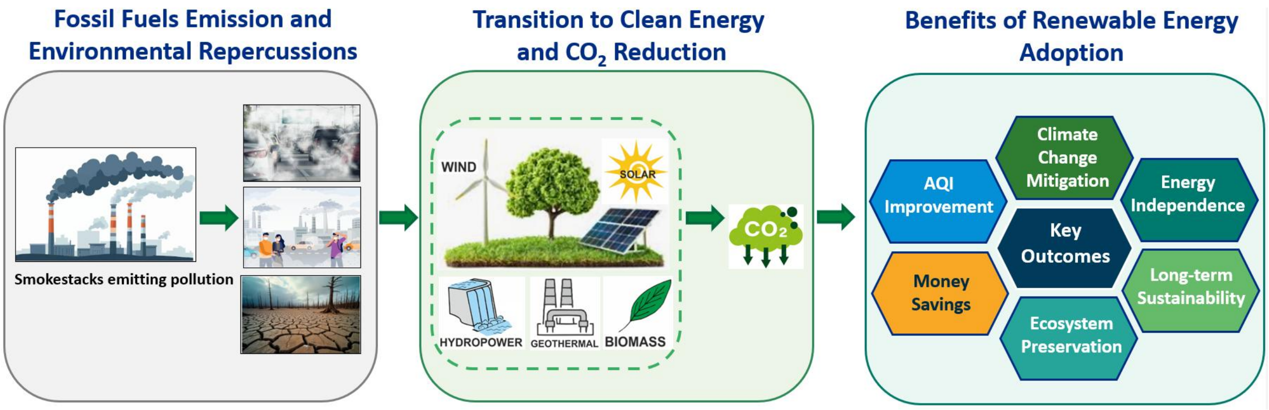

Fig. 1: Transition from fossil fuel-based emissions to clean energy adoption and the resulting environmental, economic, and sustainability benefits.

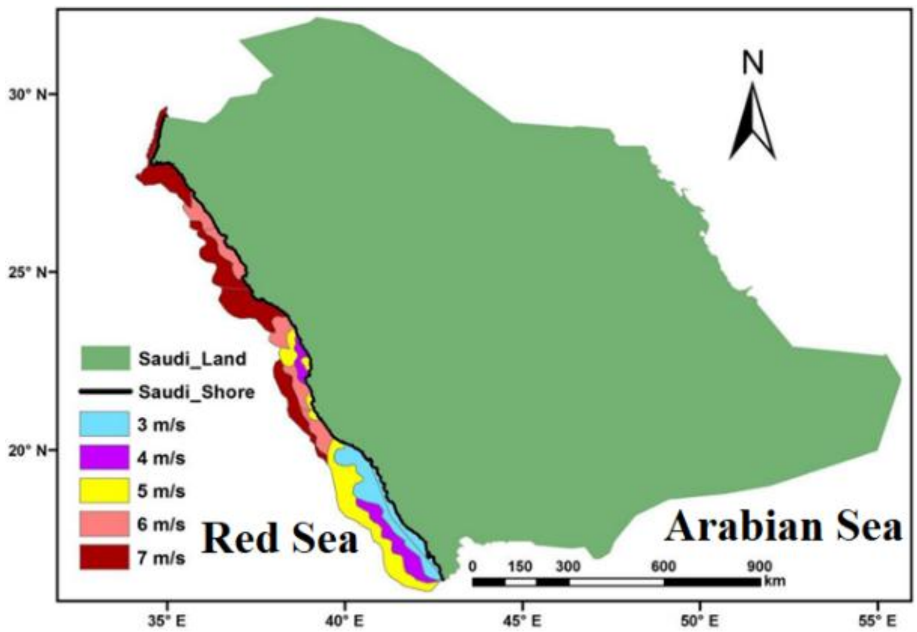

Fig. 2: Wind speed profile (3–7 m/s) along the Saudi Arabian Red Sea coast, indicating significant potential for clean and sustainable energy generation. Reproduced from.[5]

projects can fulfil energy targets that KSA has set for the greener future as well as contribute to reducing CO_2 emissions.[9] A 2.1% reduction in CO_2 emissions can only be achieved by taking new initiatives to transform conventional energy production to solar energy, thereby aligning KSA's vision 2030 goals.[10] As an example, solarized water pumps for palm tree irrigation have been suggested to address the water scarcity issues in KSA. Their estimated cost ranges between 0.013 and 0.019 $/kWh, close to the standardized cost of producing water for irrigation.[11] It is believed that energy transition in rural areas is linked with sustainable energy transformation at the national level, and the resulting substantial impact on the economies and businesses of these areas is established.[12] The widespread effects of this transition can be witnessed only if local communities are included in energy transformation plans so that their local issues and challenges may be addressed. Moreover, these energy transformation programs have demonstrated the capacity to lessen the urban-rural income gap, demonstrating the socioeconomic benefits of such activities.[13,14]

1.1 Energy mix of KSA

The KSA has long been heavily reliant on fossil fuels, particularly oil and gas, which have been the foundation of its economy and energy policies[15] and the main source of country's Gross Domestic Product (GDP), accounting 90% of the revenue generated by the country per annum.[16] It is also the main contributor to the country's energy mix. According to the data shared by Ministry of Energy (MoE), KSA, in 2019 the share of liquid fuel and natural gas to national energy mix was 51% and 49% respectively.[17] According to the report of International Renewable Energy Agency (IRENA), the total installed capacity for electricity generation of KSA in the year 2023 is 92 GW, of which 89 GW contributed by non-renewable (fossil fuels) and 3 GW contributed by renewable (Solar and wind) energy resources, with 3 percent rise in RE installed capacity.[18] KSA's total electricity generation for the year 2022 was 408,788 gigawatt-hour, of which 405,949 GWh (99%) was contributed by non-renewable and 2,839 GWh (1%) was contributed by RE resources.[18] This data shows KSA's energy sector immense reliance on fossil fuels. Fig. 3 shows the KSA's Electrical energy production percentage by form from 2015 to 2022.

The KSA's energy consumption by source between 1960 and 2030 is displayed in Fig. 4. In the past, oil dominated the energy mix, but it has since steadily decreased. Gas consumption, on the other hand, has been rising consistently since the 1970s and is now a substantial component of the energy mix. The shares of other sources, such as coal, hydro, solar, nuclear, and wind, have remained small or insignificant. Based on the IRENA Renewable Capacity Statistics 2025 report,[20] solar photovoltaic (PV) dominates Saudi Arabia's renewable energy mix, accounting for 90% of the total renewable capacity, followed by wind energy at 9% and concentrated solar power (CSP) at 1%, as shown in Fig. 5. This distribution highlights the KSA's strong focus on solar PV deployment as the primary driver of its RE adoption under Vision 2030.

In KSA, the renewable share of total energy consumption remains 0.08% up to 2021 with a 0% change in the trend over the last decade (2010 to 2021),[22] an alarming situation for policy makers and visionaries. As of 2022, 63% wind and 37% PV solar contribute to the electricity generated from RE sources (non-combustible),[22] despite the fact that KSA has tremendous potential to increase the solar-based electricity generation. Fig. 6 shows the growth of non-combustible

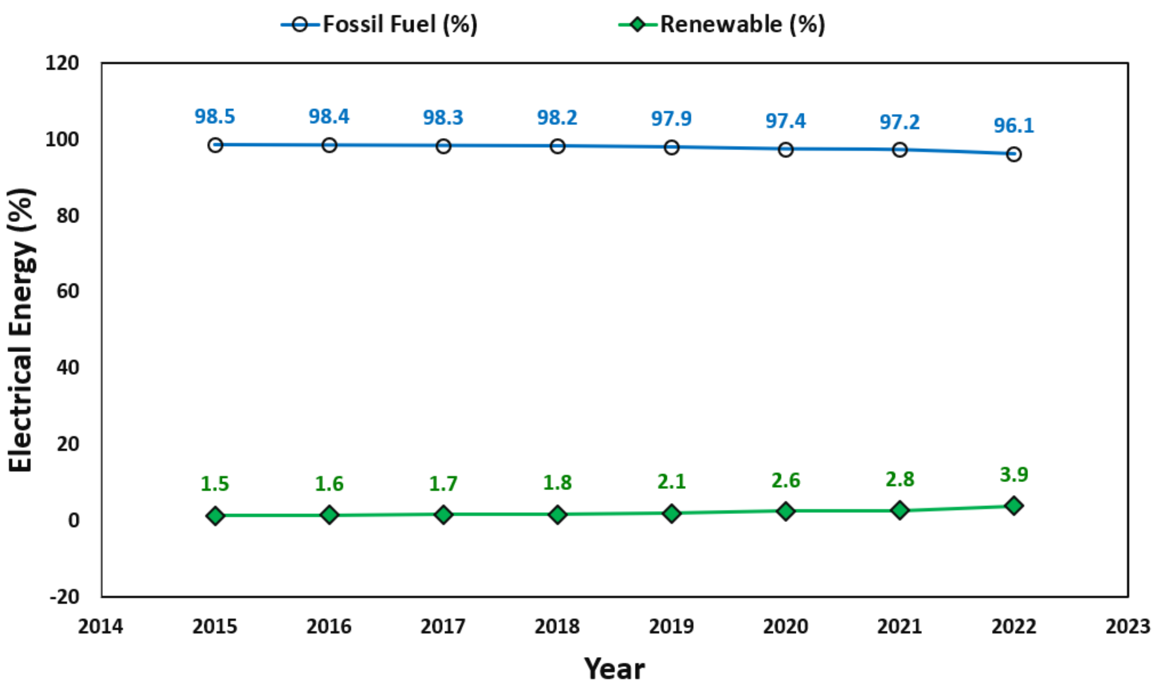

Fig. 3: The KSA's Electrical energy production percentage by form from 2015 to 2022. Reproduced from.[19]

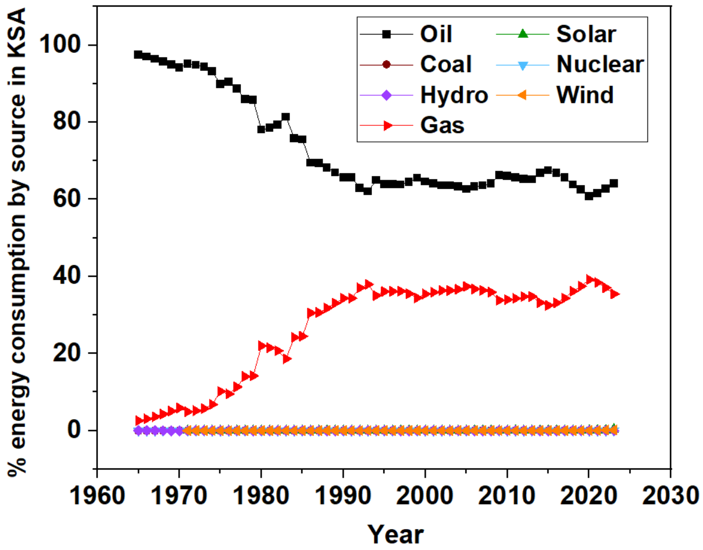

Fig. 4: Percentage share of energy consumption by source in the KSA. Reproduced from.[21]

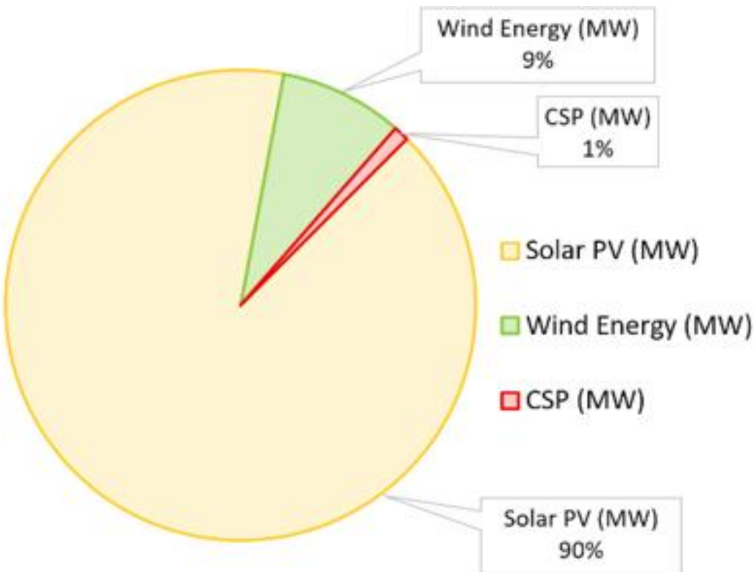

Fig. 5: Renewable energy capacity mix in KSA by technology in 2024, highlighting the dominance of solar PV. Reproduced from.[20]

Renewable Electricity Generation by Source in Saudi Arabia (2010 Onwards). In line with its Vision 2030 initiative, the KSA has set ambitious targets to source at least 50% of its power from RE by 2030, aiming to expand its capacity to 130 GW. This includes plans for 58.7 GW from solar and 40 GW from wind energy. These initiatives aim to reduce the carbon footprint in addition to the geopolitical interests of KSA, positioning it as a leader in RE within the Gulf Cooperation Council.[23] The KSA will have the highest RE targets among GCC countries by 2030, as shown in Fig. 7.

The KSA has set ambitious targets to increase the RE share in its energy mix as part of Vision 2030 and the Saudi Green Initiative (SGI). Currently, RE contributes a small but growing portion of the total energy mix, with solar and wind power as leading energy sources. Major projects such as the Sakaka Solar Power Plant (300 MW) and Dumat Al Jandal Wind Farm (400 MW) reflect key milestones in this shift. Additionally, the NEOM Green Hydrogen Project is set to promote the KSA as a global leader in hydrogen energy, further diversifying its energy mix.[24]

1.2 Motivation for sustainable energy

The population of KSA is expected to reach 68 million by 2050, expanding at one of the fastest rates in the world 234% from 2010. The unchecked economic expansion and this rapid growth are causing the demand for energy to rise sharply.[26] Electricity is closely linked to economic growth and industrial development. Electricity generation is 65% from oil, 27% from natural gas, and 8% from steam.[27] To maintain the leading role of KSA in the energy sector and meet the rapidly growing demand for energy in modernization and various industrial sectors. The Kingdom has initiated efforts to diversify its energy mix and reduce environmental degradation. A study examining KSA's commitment to RE indicates the country's strategic shift towards sustainable energy sources to reduce fossil fuel dependence.[13] Creating jobs for the KSA's increasing population is another challenge to the country's sustainable economic growth. By 2030, the current population of the KSA is projected to rise from 34 million[28] to 45 million. To accommodate the demands of this growing population, the KSA government must provide millions of new employments. This can be accomplished by making investments in training and education as well as by promoting an atmosphere that is conducive to business and draws in foreign capital.[29]

The total CO_2 emissions of KSA in the year 2022 was 605 metric-ton (Mt), of which 247 Mt of CO_2 emissions was contributed by electricity & heat generation sector, 140.8 Mt by oil and 106.2 Mt by gas generated electricity.[18] Fossil fuels (coal, gas, and oil) are not evenly distributed across the countries, and their reserves do not regenerate once they are depleted; consequently, they have been steadily approaching exhaustion due to consistent consumption. Another key reason for the shift to RE is that energy produced using fossil fuels is not clean; a lot of hazardous gases and particles are produced as byproducts, which have been damaging the ozone layer that shields the earth from harmful rays. Energy is the lifeline of an economy, and a country self-reliant in the energy sector can guarantee its sovereignty, integrity, and security. SDG 7, clean and sustainable energy for all, have received immense attention from all over the world, and all countries have declared their manifestos to shift their energy/economy/industry progressively towards clean and sustainable energy.[8] Massive installation of solar energy projects can fulfil energy targets that KSA has set for the greener future as well as contribute to reducing CO_2 emissions.[9] A 2.1% reduction in CO_2 emissions can only be achieved by taking new initiatives to transform conventional energy production to solar energy, thereby aligning KSA’s vision 2030 goals.[10]

The International Renewable Energy Agency (IRENA) reported the total installed capacity for electricity generation of KSA in the year 2023 was 92 GW, of which 89 GW was contributed by non-renewable (fossil fuels) and 3 GW was contributed by renewable (solar and wind) energy resources, with a 3 percent rise in RE installed capacity.[18] KSA’s total electricity generation for the year 2022 was 408,788 gigawatt-hour, of which 405,949 GWh (99%) was contributed by non-renewable and 2,839 GWh (1%) was contributed by renewable energy resources.[18,30]

The KSA is a rapidly developing country with high growth in population and economy. To address the challenges of sustainable and clean energy availability, climate change and stable economic growth, suggestions to take new initiatives are made.[31] The implementation of Vision 2030 has led to substantial investments in solar and wind power, exemplifying how RE can drive both environmental and economic transformation. These initiatives not only aim to reduce the nation's carbon footprint but also have significant geopolitical implications.[23] By 2030, the energy, mining, industrial, and logistics sectors must be aligned, according to their National Industrial Development and Logistic Program announced in 2019, to provide maximum contribution to the development and diversification-of-the-economy efforts of the Kingdom.

Considering the aforementioned facts and figures, KSA should prioritize its energy paradigm to shift from non-renewable to energy mix, thereby requiring an implementation of structural transformations in the energy sector. Sustainable energy is one of the most viable solutions to energy problems. KSA's landscape is supportive of sustainable solar systems and can reap its benefits. The KSA largely relies on fossil fuels resulting in highest CO_2 per capita across the world. There are certain renewable projects (green hydrogen, biogas and wind power) on the table that can be added to the energy grid; solar remains the most viable one.

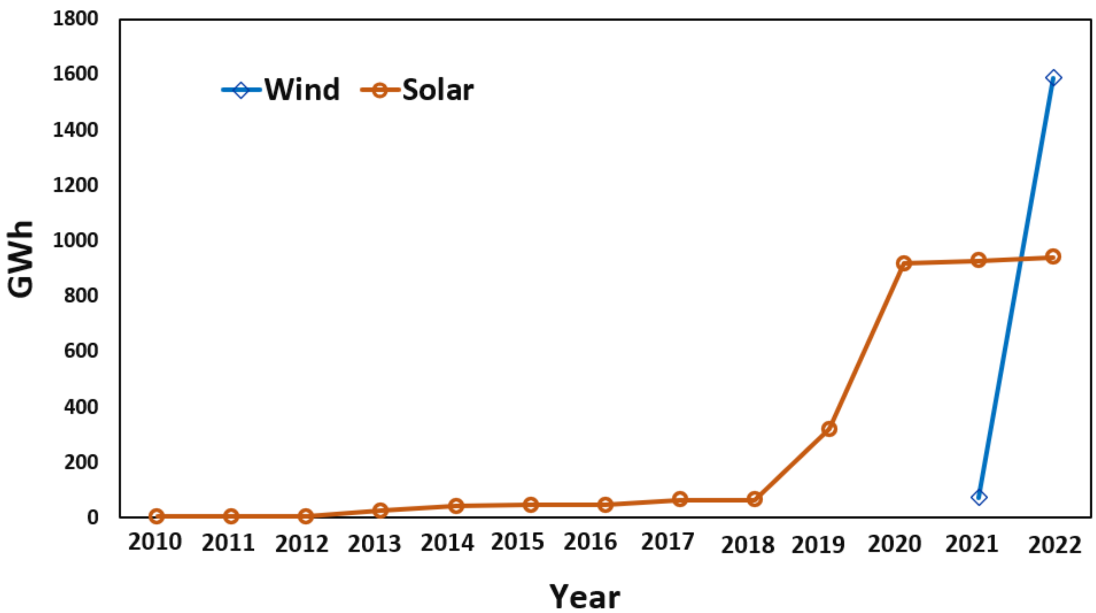

Fig. 6: Growth of non-combustible renewable electricity generation by source in Saudi Arabia (2010 Onwards). Reproduced from.[22]

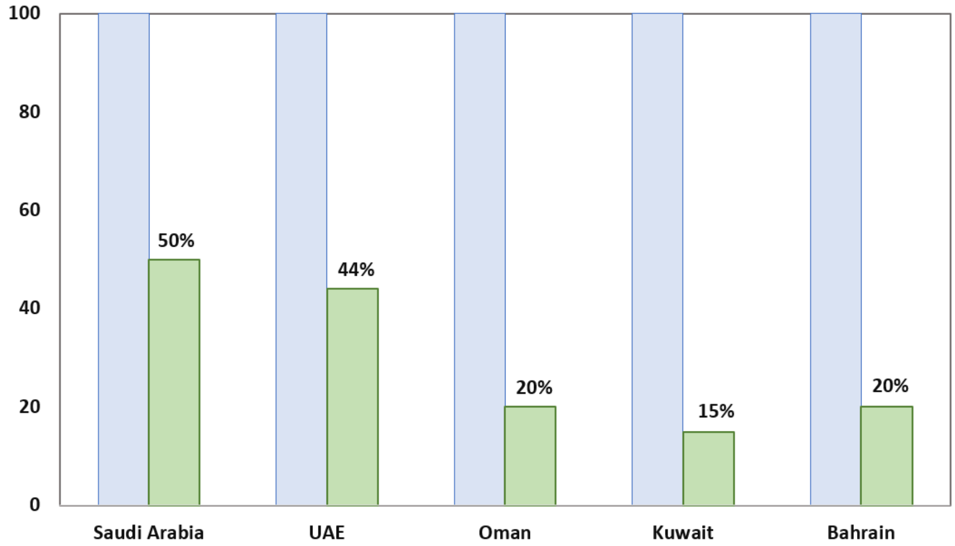

Fig. 7: Renewable energy capacity targets as a % of total energy mix. Reproduced from.[25]
Note: Target years vary by country.

The recent initiatives in the context of clean and sustainable energy transition, and current status assessment are focused in this study. The RE adoption in any country is of utmost importance in the contemporary modernized and industrial revolution era, and on top of that, REs is essential for KSA to maintain its leadership role among the middle eastern economies and the country's massive ongoing growth and high-tech projects in a variety of sectors. The primary purpose of renewable technology is to produce electricity though RE resources can be used for a variety of sectors *i.e.*; residential and commercial heating, industrial processes, and for transportation sector.[22] Reports suggest that burning biofuels (collected wood, dung, and agricultural by products) leaves detrimental effects by adding hazardous gases and particles to air therefore despite their nature of natural refill, they should not be considered the RERs when it comes to clean and sustainable energy resources.

1.3 Scientific significance and original contribution of this review

To highlight the original contribution of this review, Table 1 highlights the main features of the Saudi clean-energy transition model by their uniqueness, generalizability, and replicability. The table highlights the framework that connects Vision 2030, investment mechanisms, renewable energy deployment, smart grid modernization, hydrogen development and implementation challenges. This synthesis offers the transferable lessons learned from Saudi experience for other fossil fuel dependent economies pursuing clean and sustainable energy future.

2. Methodology and analytical framework

In accordance with Vision 2030, KSA has implemented several initiatives to diversify its energy mix and improve energy efficiency. These efforts reflect KSA's concrete steps to address climate change, reduce carbon emissions and align with the global shift toward a sustainable energy future. The key priorities of these initiatives include promoting economic diversification while ensuring long-term energy security.

This study employs secondary data collected from research articles, authentic websites and energy reports. The findings are categorized to provide a detailed analysis of recent initiatives and opportunities for sustainable energy advancement in the region. A block-level analytical framework adopted in this review is shown in Fig. 8. The framework aligns with the structure of the manuscript and shows how the review progresses from KSA's fossil fuel dependence to the transition phase and then a growing RE adoption.

3. Key dimensions of clean energy adoption in KSA

3.1 Government policies and Vision 2030 goals

KSA has initiated several large-scale RE projects to diversify the energy mix and reduce dependence on fossil fuels, in support of Vision 2030. To support a cleaner economic transition, strategies to reduce greenhouse gas emissions need to be promoted. One of the main targets is expanding RE to cover up to 50% of energy production. Another major consideration is the Circular Carbon Economy (CCE), a mechanism that reduces, reuses and recycles CO_2 to minimize impacts on the environment. By regulating emissions from the industrial and energy sectors, investing in Carbon Capture, Utilization, and Storage (CCUS) technology can help the KSA in supporting this initiative. Waste management improvements, particularly efficiency efforts in Riyadh, are another crucial feature of this approach. Waste management is identified as one of the primary operational pathways for KSA's circular economy transition under Vision 2030.[32] However, outcomes remain limited due to landfill dependence and weak institutional and regulatory implementation. The gradual shift of energy-intensive sectors from fossil fuels to RE can achieve KSA's net-zero carbon emission target by 2060.[33]

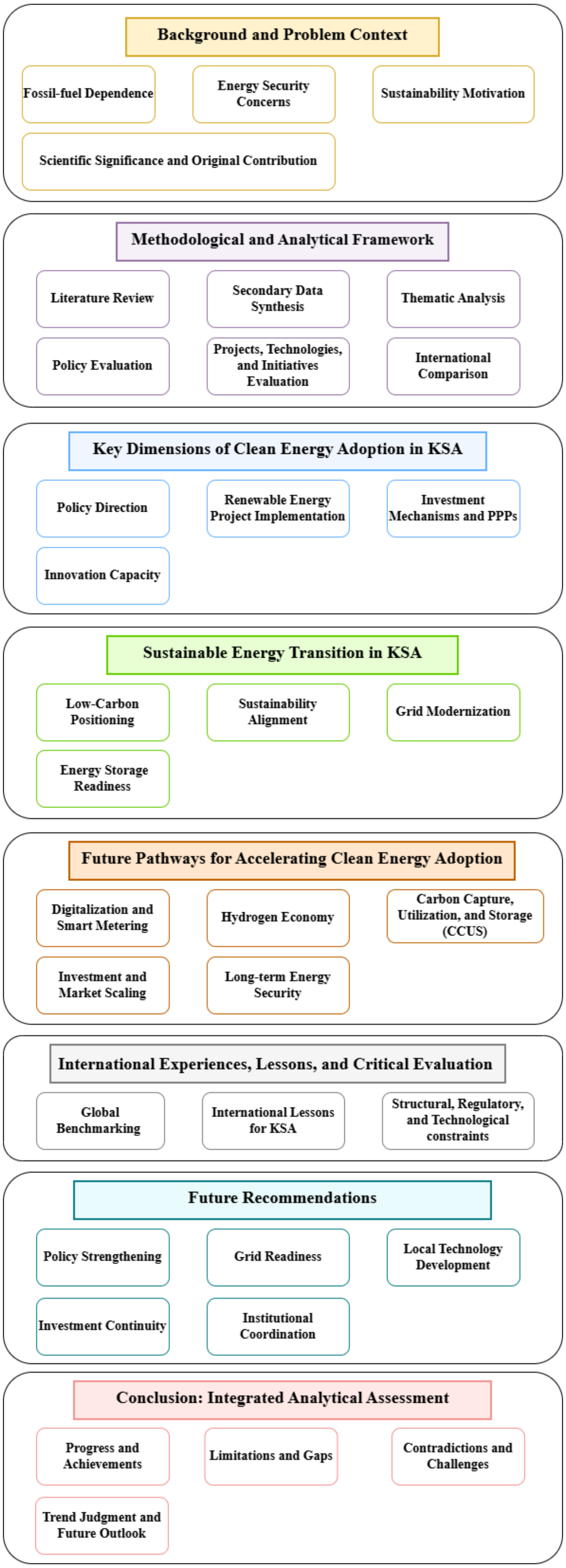

Fig. 8: Block-level analytical framework for assessing KSA's clean energy transition.

Table 1: Generalized and replicable features of the Saudi clean energy transition model.

Saudi model feature	Evidence from KSA	Generalizable lesson	Replicability condition
Vision-led policy direction	Vision 2030, SGI, NREP, net-zero 2060	Long-term national targets can coordinate energy transition	Requires stable policy commitment
State-backed investment	PIF, green finance, PPPs	Public capital can de-risk early-stage clean-energy projects	Requires strong financing institutions
PPP-based delivery	Sakaka, Dumat Al Jandal, NEOM hydrogen	Private sector participation accelerates deployment	Requires bankable contracts and PPAs
Technology integration	Smart meters, AMI, smart grids, storage	Digital grids are essential for renewable integration	Requires grid modernization
Resource-based specialization	Solar, wind, hydrogen, desalination-linked storage	Countries can build transition pathways around domestic resources	Requires resource mapping and infrastructure
Challenge-aware transition	Storage, water scarcity, policy gaps, imported technology	Energy transition must address local constraints	Requires adaptation to national context

Building on these policy directions, the National Renewable Energy Program (NREP) aims to develop 58.7 GW of RE capacity by 2030, with 40 GW from solar and 16 GW from wind power.[34-36] The Sakaka Solar Power Plant, with a capacity of 300 MW, and the Dumat Al Jandal Wind Farm, with a capacity of 400 MW,[37] exemplify notable projects.

Besides generation-side initiatives, KSA is heavily investing in advanced metering infrastructure (AMI).[38] The AMI offers several operational benefits, such as reduced operation and maintenance costs, minimized losses, electricity savings, improved network planning, and support for smart grid initiatives. It also provides strategic benefits, including enhanced customer satisfaction, support for demand response programs, and facilitation of RE source integration, making it a valuable long-term investment. To improve energy management, and billing accuracy considering Vision 2030, Saudi Electric Company (SEC) claimed to install 10 million smart meters by 2025.[39] This initiative is likely to reduce unplanned outages and extend the lifespan of grid infrastructure.

The KSA, therefore, has several policies and strategies in place that support its projects by promoting the adoption of RE and private sector participation. The introduction of Power Purchase Agreements (PPAs) makes investment more attractive by ensuring long-term financial viability for RE developers. In tandem with this, the Saudi Green Initiative (SGI), launched in 2021, aims to plant 10 billion trees and actively cut carbon emissions by 278 million tons annually as an effort to curb the environmental effects of energy production.[40]

3.2 Renewable energy projects (Solar, wind, and hydrogen)

KSA initiated several large-scale RE projects to meet the long-term goals of its Vision 2030 strategy to diversify its energy mix and reduce reliance on fossil fuels. Solar energy plays a central role in this transition, with NEOM's Helios Green Hydrogen Project being one of the largest initiatives worldwide.[41] The NEOM Green Hydrogen project, aiming to produce green ammonia at a large scale in 2026, was seeded with USD 6.1 billion from 23 local and international banks and financial institutions, totaling USD 8.4 billion. In order to maintain continuity and stability of the resources and assets, a 30-year agreement of the value of USD 6.7 billion was set between the potential stakeholders to secure all green ammonia that is going to be produced. The green ammonia produced from this project is going to be used in electrolysis to produce green hydrogen, positioning KSA as a global leader in green hydrogen production. The Sakaka Solar Power Plant, the first utility-scale solar photovoltaic (PV) project in the country, is another major initiative with a production capacity of 300 MW and reducing 530,000t of carbon dioxide (CO_2) emissions annually.[42] In Sakaka Solar Power Plant is claimed reducing 430,000t of CO_2 emissions annually.[43] Another initiative, the Sudair Solar Plant, one of the largest in the region, is expected to generate 1.5 GW of clean electricity, contributing to the agenda of increasing RE capacity.[44] They aim to generate 50% of their electricity from renewables by 2030, reducing carbon emissions and supporting sustainable growth. These projects comply with KSA's future strategy to generate 50% of its electricity from renewables by 2030, thereby lowering carbon emissions and promoting sustainable energy growth. However, policy and regulatory clarity, grid integration readiness, financial support mechanisms, land-use planning, stakeholder participation, technical innovation, and monitoring frameworks are critical to large-scale solar PV implementation in KSA.[45]

Apart from solar energy, wind power is also becoming a viable RE source in KSA. With a 400 MW[46] capacity, the Dumat Al-Jandal Wind Farm is KSA's first large-scale wind energy project. It is expected to reduce CO_2 emissions by 988,000 tons annually by powering 70,000 homes. The Saudi government is also exploring offshore wind possibilities to boost the country's RE portfolio. Furthermore, hydrogen energy is emerging as a critical component of the KSA's clean energy transition.[47,48] There are plans in place by the NEOM Green Hydrogen Project to engage international partners in the production of hydrogen, reaching the 650 tons per day mark by 2025, while making use of the country's enormous solar and wind resources.[49] Such initiatives testify that KSA is striving toward sustainable energy, CO_2 emission reductions, and being a key player in the RE market worldwide. If this program is incorporated into advanced grid infrastructure with storage technology, KSA is anticipated to further accelerate the 2060 net-zero goal.[50] Fig. 9 presents the solar and wind energy projects installed and commissioned between 2019 and 2024. The year-wise progression suggests a transition from pilot-scale deployment (2019–2022) to large-scale commercialization (2023–2024).[51]

For safe transportation, conversion of hydrogen to green and blue ammonia is under consideration. To supply hydrogen, KSA is collaborating with countries with strict decarbonization targets and high energy demands, though challenges related to cost, resources, and knowledge still need to be resolved. For instance, green hydrogen production remains expensive due to high infrastructure and electrolysis costs.[24] Electrolysis requires a significant amount of water, and the production process relies on imported raw materials. Moreover, KSA faces a shortage of skilled professionals in hydrogen technologies. Therefore, resolving these issues through lower costs, water management, domestic mineral development, and workforce training is important for KSA's hydrogen ambitions.[24]

3.3 Public-private partnerships and investment trends

The KSA is strengthening Public-Private Partnerships (PPPs) to accelerate sustainable energy adoption in line with Vision 2030 and the Saudi Green Initiative (SGI). The National Renewable Energy Program (NREP) has facilitated private-sector involvement in large-scale projects, such as the Sakaka Solar Power Plant and the Dumat Al Jandal Wind Farm, both developed through competitive bidding processes. Similarly, the NEOM Green Hydrogen Project, a $5 billion joint venture between ACWA Power, Air Products, and NEOM, highlights the country's commitment to green hydrogen production. These initiatives demonstrate how PPPs attract both foreign and domestic investment, reduce the government's financial burden, and enhance the expertise of the KSA's industrial sector in the field of RE.

Trends of heavy investment in green energy projects indicate KSA's commitment to achieving clean and sustainable energy goals. However, the evaluation of RE investment should consider some other important factors in addition to focusing on revenue generation. In this context, economic viability, environmental impact, social acceptance, technological feasibility, regulatory stability, policy uncertainty, and market risks matter.[52] The KSA's Public Investment Fund (PIF) plays a vital role in funding green energy infrastructure. In parallel, private investors benefit from regulatory frameworks, such as Power Purchase Agreements (PPAs), that ensure financial stability for ongoing and future RE projects. The government promotes green bonds and sustainability-linked financing to attract international investors.

3.4 Research and development (R&D) in renewable technologies

The KSA is pursuing R&D in RE as part of its Vision 2030 goal. Institutions such as King Abdullah City for Atomic and Renewable Energy (K.A. CARE), King Abdulaziz City for Science and Technology (KACST), and the Saudi Energy Research and Development Center (SERDC) are contributing to the development of RE technologies. Their work focuses on improving photovoltaic efficiency, advancing energy storage systems, and developing hydrogen production technologies. Moreover, the SGI and NEOM's Hydrogen project

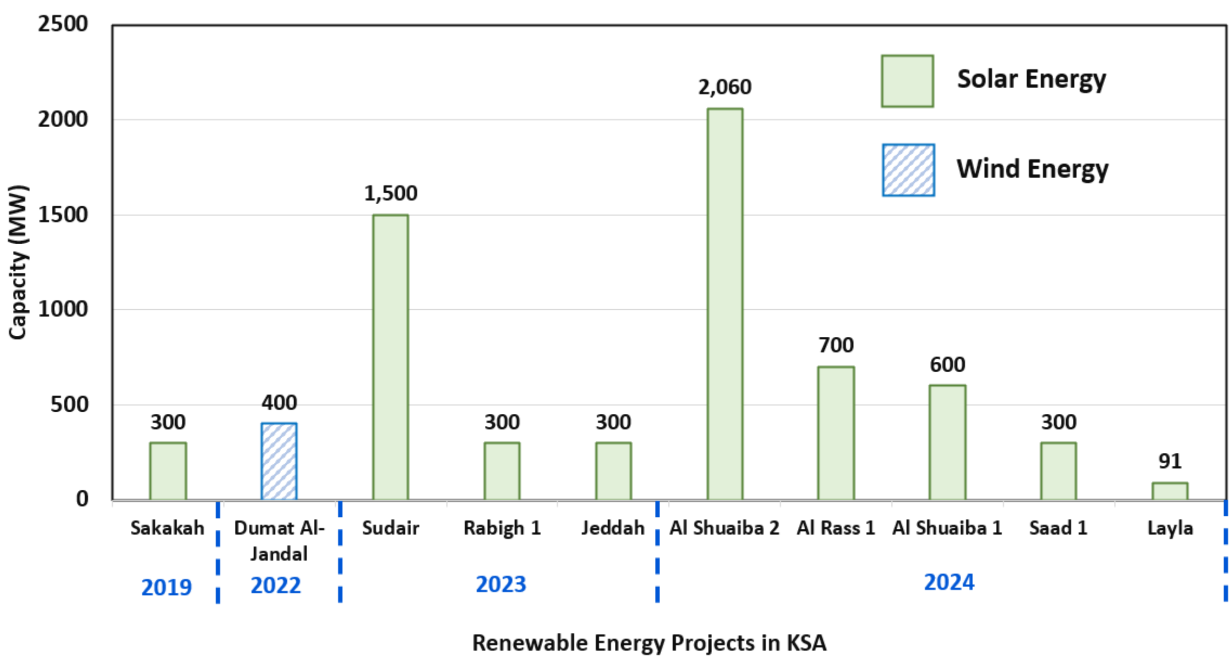

Fig. 9: Renewable energy projects commissioned in KSA between 2019 and 2024. Reproduced from.[51]

partnerships indicate a growing institutional commitment to clean energy innovation. To support the commercialization of RE technologies, tax holidays and grants for the private sector have been introduced. Investments in next-generation solar panels, wind turbine optimization, and hydrogen fuel development are increasing, with projects such as the Solar Energy Research Program at KAUST supporting research-based innovation.[53]

4. Sustainable energy transition in KSA

At present, the KSA is moving gradually toward RE sources, supported by the country's Vision 2030 initiative. This transition is based on three key areas: sustainable technologies, supporting frameworks, and energy-efficiency measures. Together, these areas aim to reduce dependence on fossil fuel systems and improve energy efficiency. The following sections discuss the main aspects of this transition.

Renewable energy potential: Solar energy has emerged as the most favorable alternative for sustainable energy transition in KSA, as indicated by a fuzzy TOPSIS-based evaluation, which ranks it highly among other options.[54] The word TOPSIS is derived from the Technique for Order of Preference by Similarity to Ideal Solution, and is a popular multi-criteria decision-making method.

Energy storage solutions: The integration of solar photovoltaic (PV) systems with energy storage is being explored, particularly in the healthcare sector, where it can provide up to 15% of electric consumption, reducing emissions and reliance on diesel generators.[55]

Building energy efficiency: Research on polycarbonate windows with nanogel has shown a 29% reduction in energy consumption, highlighting the importance of sustainable building designs in improving thermal performance.[56]

Policy and framework development: The application of Bayesian Belief Networks (BBN) to assess energy sustainability indicators has provided insights into the factors influencing KSA's energy policies, emphasizing the need for a diversified energy mix and reduced CO_2 emissions.[4] Despite the KSA's ongoing progress in the field of sustainable energy, challenges must be resolved before these technologies can be fully integrated into current frameworks. The need for further research and development in sustainable entrepreneurship is also critical to foster innovation and economic resilience in this evolving landscape.[57]

4.1 KSA in the global low-carbon transition

The KSA is increasing its involvement in climate diplomacy and sustainable energy innovation. Its participation in the Global Methane Pledge, Circular Carbon Economy framework, and Middle East Green Initiative reflects its policy focus on emissions reduction, energy efficiency, and regional environmental cooperation. However, continued dependence on fossil fuels, water scarcity, and energy-intensive industries remain key challenges. Strengthening policy frameworks and investing in sustainable infrastructure will be essential to support KSA's transition toward a low-carbon economy.

4.2 National and global sustainability initiatives in KSA's energy transition

The KSA has advanced its sustainability agenda by aligning Vision 2030 with global frameworks such as the UN SDGs. Through SGI and NREP, it aims to expand RE, reduce emissions, diversify the economy, achieve net-zero emissions by 2060, and generate 50% of electricity from renewables by 2030. Through partnerships in the Global Methane Pledge (GMP) and initiatives under the Circular Carbon Economy (CCE) framework,[58] the country is working to mitigate greenhouse gas (GHG) emissions and enhance energy efficiency. The Middle East Green Initiative (MGI) extends its sustainability efforts beyond national borders, fostering regional cooperation on environmental policies and clean energy development.

4.3 Smart grid and energy storage developments

The KSA is deploying smart grids and energy storage solutions to make its electricity system more efficient, reliable, and capable of supporting higher renewable energy integration. Investments in advanced metering, Artificial Intelligence (AI)-based demand response, and decentralized energy management can reduce transmission losses and provide the flexibility needed for the sustainable energy transition. In addition, KSA's partnerships with international technology companies can support research and development in energy storage technologies, contributing to grid modernization and sustainable energy development in the region.

Energy storage is expected to play a central role in the RE transition in the KSA by addressing renewable intermittency and improving grid resilience. This includes investment in battery energy storage systems (BESS), pumped hydro storage (PHS), and hydrogen-based storage systems to store excess power produced from solar and wind farms. For example, PHS, particularly through the storage of desalinated water, could serve as a promising long-duration storage option for Saudi Arabia by reducing summer electricity demand and supporting renewable-energy grid balancing.[59] Similarly, the NEOM Green Hydrogen Project is expected to support the storage and use of RE.

5. Future pathways for accelerating clean energy adoption

Effective strategies for the KSA's transition toward a sustainable energy future need to be implemented while addressing existing challenges. A route aligned with Vision 2030 can be set by adapting technological innovation, planned investment, and long-term effective policies.

5.1 Technological innovations for energy integration

The KSA uses advanced technologies to seamlessly integrate into its power grid, ensuring efficiency, reliability, and sustainability.

5.1.1 Blockchain-enabled smart metering system

Without requiring human interventions, smart energy meters are IoT devices to automate energy recordings. For efficient utilization, they are combined with blockchain technology, and such a decentralized automated energy-readings/billing system can be developed in which each entry/transaction is encrypted and cannot be tampered with. AI- and IoT-powered smart grids monitor real-time energy, predict maintenance, automate demand response, and optimize energy distribution.[60] To balance the variability of solar and wind energy, the country is deploying large-scale energy storage systems and pumped hydro storage, in addition to investing in blockchain-based energy trading platforms.[61] These initiatives will allow decentralized and transparent transactions between energy producers and consumers[62] and virtual power plants,[63] further enhancing grid flexibility and innovation.[64-66]

Blockchain is implemented through software and hardware to maintain structured data, validate and timestamp it, and link it to ensure immutability and transparency. Each block stores transaction data with a unique code for the current and the previous blocks, creating an unbreakable chain as shown in Fig. 10. The image shows 3 blocks of transactions recorded in blockchain; each block records the day's solar energy generation and consumption and related attributes. There is a timestamp to record the exact time of block generation with a mechanism. The blocks are linked together through hash values.[62,64]

Blockchain combined with smart grids can improve energy efficiency, security, and transparency via peer-to-peer (P2P) trading, decentralized ledgers, and smart contracts. Its adoption is driven mainly by cost savings, regulatory support, and innovativeness, with less influence from competitive pressure and traceability.[61] Blockchain supports real-time tracking, reduces costs, and minimizes intermediaries,[67] although regulatory uncertainty and scalability issues remain key challenges. These findings can help policymakers support smart grid digitalization and improve energy infrastructure planning.

Fig. 11 shows a blockchain-based peer-to-peer energy trading process. The process begins when the energy seller generates a smart contract and offers surplus energy for bidding. Consumers submit bids, and the highest bidder receives the electricity. The buyer then makes payment through blockchain, which validates and records the transaction in new data blocks. This process supports transparency, security, and decentralization throughout energy trading.[68]

5.1.2 Hydrogen production and carbon capture technologies

Hydrogen production and carbon capture technologies are important components of decarbonization. Innovation in these technologies is also shaping the KSA's clean energy development. For instance, the NEOM Green Hydrogen Project, one of the world's largest hydrogen production projects, aims to produce green hydrogen at scale and support the transition to a hydrogen-based economy. Carbon Capture, Utilization, and Storage (CCUS) technologies are being integrated with fossil fuel plants to reduce emissions while maintaining energy security. Furthermore, research into next-generation photovoltaic (PV) cells, floating solar farms, and concentrated solar power (CSP) technologies is increasing the KSA's solar capacity. Through these innovations, the country is strengthening sustainable energy integration and smart energy management.

5.2 Investment and market opportunities in the clean energy sector

Clean energy presents increasing investment opportunities, driven by technological advancements, policy incentives and global sustainability goals. Governments and private investors are funding solar, wind, hydrogen and energy storage projects, leveraging green bonds, carbon credits, and tax incentives. Emerging markets provide great promise for the future because of advancements in energy consumption and decarbonization, especially in the Middle East, Africa, and Asia.

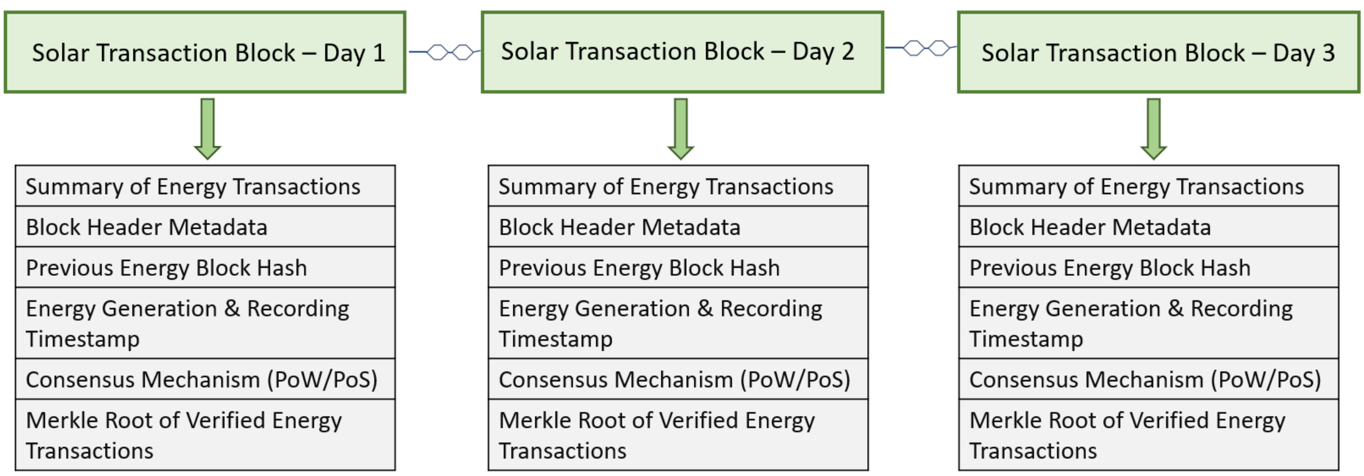

Fig. 10: Blockchain-based framework for transparent solar energy monitoring and verification. Reproduced from.[62]

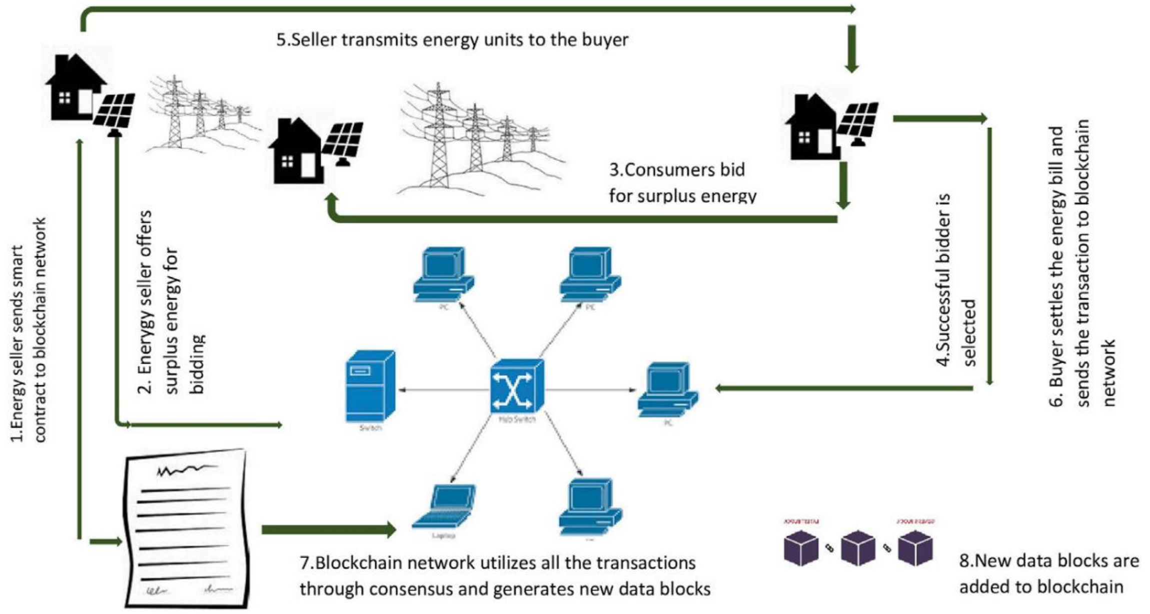

Fig. 11: Blockchain-enabled peer-to-peer energy trading process between seller and consumer. Reproduced from.[68]

Smart grids, electric mobility, and digital energy trading are attracting growing investment beyond traditional renewables. AI, blockchain, and IoT can improve energy efficiency and grid management, while net-zero goals are driving investment in green hydrogen, battery storage, and carbon capture, supported by climate policies and Environmental, Social, and Governance (ESG)-focused financing.

5.3 Long-term security strategies

A diverse, resilient, and low carbon energy mix is necessary for sustainability and long-term energy security. Investments in green hydrogen, carbon capture, and energy efficient technologies are important to achieve net zero emissions. For instance, to incentivize electric supply companies, tax reduction proportional to their low carbon emissions could be announced at the national level. Similarly, electric utility suppliers may announce incentives or favorable policies for consumers who utilize electricity units below a certain threshold and maintain it for consecutive months. Moreover, local renewables such as microgrids can meet their energy demands independently and may reduce the burden on the national grid, leading to a sustainable and reliable network. The focus is also on enhancing supply chains, building stronger infrastructure and boosting regional collaboration.

6. International experiences and lessons for KSA

To assess the ongoing progress of KSA's energy adoption, KSA's assets are benchmarked against international competitors. These countries use different strategies, including policy-driven market reforms and the use of natural resource revenues for sustainable investments. Including such comparisons in this research can help KSA identify relevant international practices and strengthen its clean energy transition.

Fig. 12 highlights the top ten Sovereign Wealth Funds (SWFs) by shareholding and net worth. Norway's Government Pension Fund Global (GPFG) shows how oil revenues can be converted into long-term economic and environmental resilience. Built through careful policy planning, fiscal discipline, and overseas investment, the GPFG indicates that resource wealth can support sustainable development when backed by strong institutions and prudent wealth management.[69-71]

Established in 1990 to manage petroleum surplus, the GPFG has grown into the world's largest sovereign wealth fund, valued at approximately United States Dollar (USD) 1.7 trillion by 2025 and holding stakes in nearly 9,000 global companies.[72] Norway strategically restricts the domestic use of these revenues, investing primarily abroad to avoid economic overheating, while channeling returns into long-term social and environmental priorities.

Due to its large capital base, the GPFG plays an important role in Norway's green transition. While the GPFG has generally followed a passive investment approach, it has the financial capacity to support climate-aligned investments.[73] Norway can contribute to the goals of the European Green Deal while also ensuring long-term returns for its population by channeling investments into sectors such as clean energy, circular economy, and green innovation within the EU.

The energy transformation, "Energiewende," is an ongoing project by Germany that purports to replace fossil fuels and nuclear energy with RE generation (wind, solar, and hydropower). The policy aims towards sustainable, low-carbon energy and climate protection by reducing the utilization of hydrocarbons and greenhouse gases till the year 2050. Initially, phasing out coal and nuclear power plants and expanding renewable and grid-based energy were key objectives of the project, which later on expanded its goals beyond just energy generation.

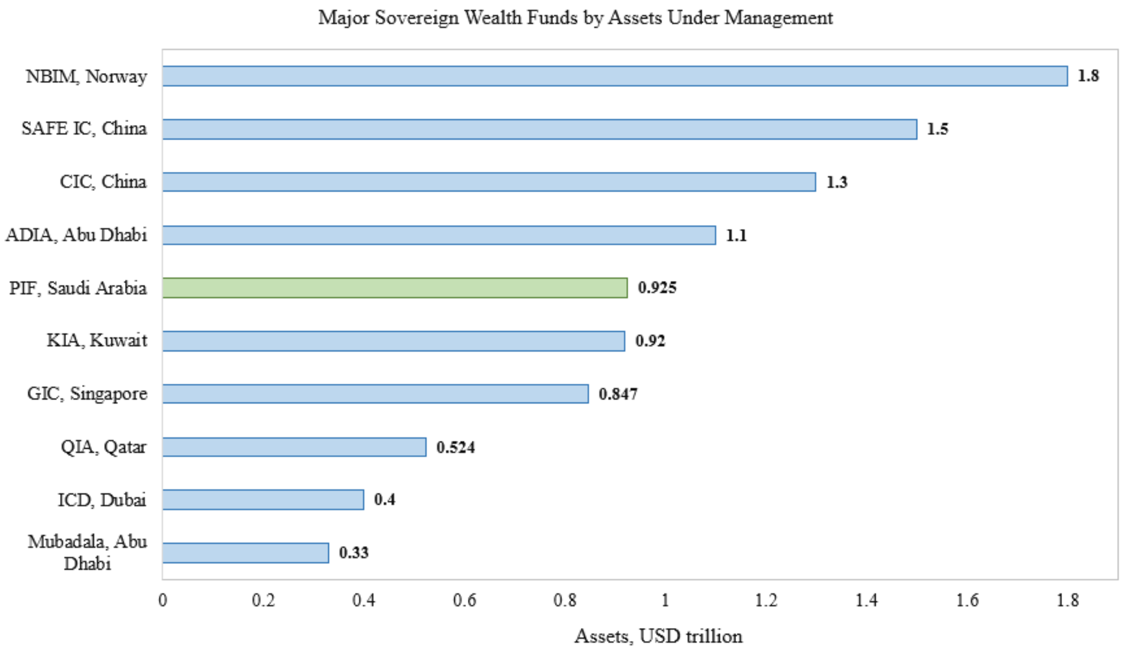

Fig. 12: World's largest sovereign wealth funds (SWF), highlighting the dominance of fossil fuel–rich countries in global asset rankings. Reproduced from.[74] Saudi Arabia's PIF: USD 0.925 trillion.

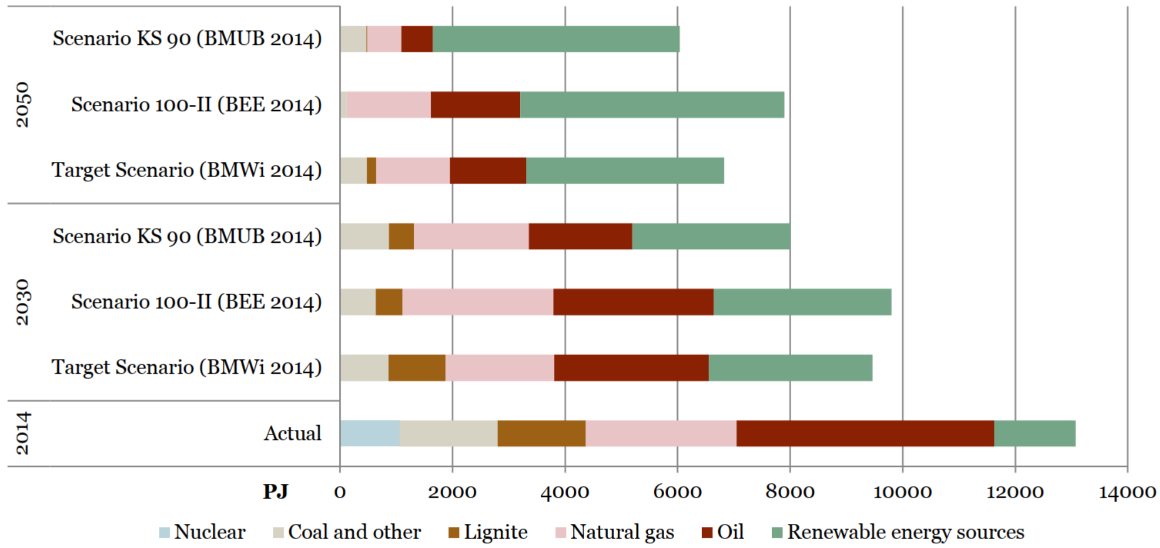

Fig. 13: Comparison of primary energy supply in 2014 and projected scenarios for 2030 and 2050 in Germany, highlighting shifts in energy sources and the decline in total energy demand across various policy pathways (in PJ/a). Fossil fuel use declines significantly, while RE gains prominence in all scenarios. Reproduced from.[78] Annual energy consumption in PJ refers to the total energy consumption across all sectors, including electricity, heating, transportation fuels, and industrial energy use.

Germany's Energiewende, focused on renewables and the shutting down of coal and nuclear power plants, is considered a climate policy.[75] However, experts' findings highlight the broader vision and additional goals other than combating climate change. A major portion of the policy remains valid even if climate change is not the focus.[76] Energiewende, and particularly the development of solar PV, led Germany to the global top in wind generation till 2008 and solar power generation in 2013. The country's economy observed a 45% rise while reducing the power consumption by 22%.[77] Fig. 13 presents the projected decline in primary energy consumption from 13,000 Petajoule (PJ) in 2014 to between 6,000 and 8,000 by the end of 2050.[78] The data presents a drop of around 80% in CO_2 emissions from the combustion of hydrocarbons as compared to the year 1990. The outcomes strengthened the idea of achieving economic growth in parallel with lessening the GHG emissions. Under the umbrella of Energiewende, Germany supports the deployment of green industry and drives innovation in key sectors that enable the energy transition, including advancing technologies such as battery storage systems, heating, transportation, and green hydrogen production and investing in research & development for the fields.

Masdar, an Emirati state-owned RE firm founded in 2006, has played a key role in promoting the UAE's global sustainability goals by constructing RE projects in over 40 countries. It aims to reach 100 GW of renewable capacity and become a leading green hydrogen producer with green hydrogen production of 1 million tons/year by 2030.[79,80] The strategy targets an energy mix that combines renewable, nuclear, and clean energy sources to meet the UAE's economic requirements and environmental goals as follows: 44% clean energy, 38% gas, 12% clean coal, and 6% nuclear.[80]

China, being a global leader in RE deployment, faces the dual challenge of maintaining growth while addressing the environmental and social imbalances of its export-led model. China needs to transform its strategy from export- and investment-led growth to a more balanced, inclusive, and long-lasting one.[81] To achieve long-term economic and ecological stability, structural changes must be implemented to increase domestic consumption, strengthen environmental protection and improve social equity, with a focus on growth quality.

The study in explores how economic growth relates to sustainable development in China, India, Pakistan and Bangladesh using indicators such as GDP, CO_2 emissions, renewable energy use, foreign direct investment (FDI) and urbanization.[82] It finds that China is making stronger progress through renewable investment and carbon reduction efforts, while India is improving but still faces sustainability challenges. Pakistan and Bangladesh lag behind due to limited renewable adoption, weaker institutions and continued reliance on fossil fuels.

The KSA can draw valuable insights from global energy transition strategies to boost its own sustainable development and economic diversification, as presented in Table 2.

Table 2: Comparative lessons from international energy transition models for KSA

Country	Main transition strategy	Strength	Limitation	Lesson for KSA
Norway	Uses GPFG to convert oil wealth into long-term resilience.	Strong wealth management and fiscal discipline.	Limited domestic renewable restructuring.	Use PIF/oil revenues for clean energy and innovation.
Germany	Energiewende expands renewables, grids, storage, and green hydrogen.	Strong policy, innovation, and emission reduction.	Complex coal/nuclear phase-out and grid balancing.	Pair renewables with grid upgrades, storage, and policy stability.
UAE	State-led clean-energy diversification through Masdar, nuclear, and hydrogen.	Strong institutions and global RE investments.	Continued gas and fossil-economy dependence.	Strengthen clean-energy institutions and partnerships.
China	Large-scale RE deployment with clean-tech manufacturing.	Global scale in RE deployment and manufacturing.	Environmental imbalance and fossil-fuel reliance.	Build local RE manufacturing with stronger governance.
KSA	Vision 2030-led solar, wind, hydrogen, PPPs, and smart-grid transition.	Strong resources, PIF support, and hydrogen potential.	Fossil dependence, low RE share, storage/grid limits, and water scarcity.	Combine wealth discipline, policy stability, institutions, and industrial scaling.

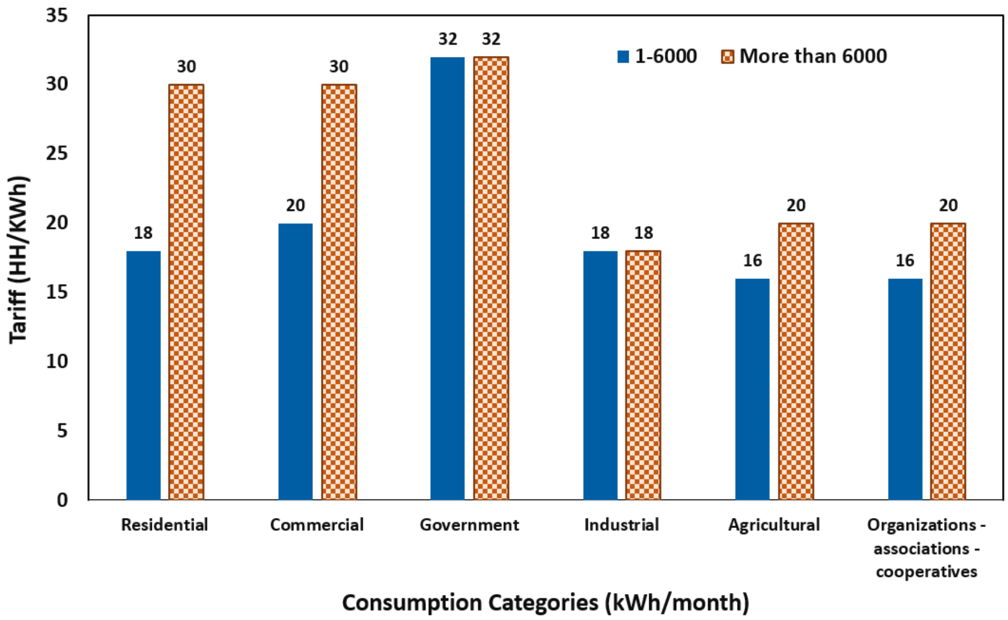

Fig. 14: Electricity tariffs across different consumption categories in the Kingdom of Saudi Arabia (KSA) for various sectors, categorized by monthly usage: 1-6000 kWh and more than 6000 kWh. Reproduced from.[83]

7. Challenges to sustainable energy adoption in KSA

7.1 Policy and regulatory

The tariff structure in the KSA aligns with economic growth and sustainability goals,[83] as shown in Fig. 14. Residential and commercial sectors will see the biggest price increases for high usage, increasing energy efficiency. The government sector maintains continuously high tariffs, regardless of consumption, to ensure public-sector accountability. Industrial tariffs are steady and cost-effective, thereby promoting economic growth. Agricultural and organizational tariffs are the lowest, with a modest increase for increasing usage, making it possible to maintain important services at a reasonable cost.

7.2 Technological limitations

The KSA has been working towards the path of upholding clean and viable energy across its KSA-Vision 2030 initiative, which aims to diversify the country's economy and minimize the use of fossil fuel. However, like other nations, it has several hurdles in its technological advancement concerning clean energy adoption.

Solar and wind energy, being two major RE sources in the current KSA energy plans, are intermittent in nature. Intermittent generation of energy due to weather conditions and daylight unavailability affects the stability and reliability of the grid.[84] The lack of cost-effective and scalable energy storage technologies are the main barriers. While battery storage is improving, it has a long way to go before it could be truly economically viable and add capacity to store large amounts of energy for extended periods.[85]

The existing grid infrastructure in KSA was primarily built for centralized fossil-fuel-based generation. Integration with decentralized renewable power generation requires huge upgrades in smart grid technologies and advanced management systems.[86,87]

The KSA relies heavily on imported technologies for RE projects, such as solar panels and wind turbines. This dependence increases costs and limits the development of a local RE industry.[88] Some RE technologies like concentrated solar power (CSP) requires a huge amount of water for cooling processes, which is a scarce resource in the KSA. This limits the feasibility of certain clean energy solutions.[89]

Challenges include a stronger link between industry and academia and adaptation to technology in the extreme climate that is present in the KSA. Long-term sustainability of energy would rely on greater protection for intellectual property and a very vibrant startup ecosystem in renewable technologies. A major challenge for KSA's sustainable energy transition is the shortage of skilled workforce, which hinders the effective integration of REs and circular economy practices under Vision 2030.[90]

8. Future recommendations

Despite the progress in grid integration, storage capacity and policy execution remain the main challenges. The economy's continued dependence on oil and historically low energy prices have also slowed the RE transition. However, government initiatives, Power Purchase Agreements (PPAs) and foreign investment are helping to accelerate the process for adoption. With sustained efforts, the KSA can emerge as a global RE leader while balancing economic growth with sustainability.

9. Conclusion

KSA has ambitious renewable energy targets, but current electricity generation is still dominated by fossil fuels. This study analyzed KSA's transition toward clean and sustainable energy through a detailed examination of existing initiatives, national policies, frameworks and ongoing RE projects under Vision 2030. The analysis shows that the Kingdom has made real progress in diversifying its energy mix by expanding solar, wind and new hydrogen projects. This is thanks to changes in government policies, more investment opportunities and investment in research and development. These efforts reflect KSA's strategic position within the global low-carbon transition and its commitment to aligning national energy goals with international sustainability agendas.

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Data Availability Statement

Data will be made available on request.

Conflict of Interest

The authors declare no conflict of interest.

Supporting Information

Not applicable.

CRediT Statement

Ahmed Salim and **Zafar Ullah:** Writing - Original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Wazie M. Abdulkawi:** Writing - Review & editing, Validation, Investigation, Conceptualization, Funding, Supervision. **Sajjad Ur Rehman:** Writing - Review & editing, Validation, Investigation, Conceptualization, Supervision. **Median Zeghid** and **Hassan Yousif Ahmed:** Writing - Review & editing, Validation, Investigation.

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