Review

Saudi Arabia’s Journey toward a Renewable Future

Saad F. Al-Gahtani 1,2

1 Electrical Engineering Department, King Khalid University, Abha 61421, Saudi Arabia; saljbar@kku.edu.sa
2 Center for Engineering and Technology Innovations, King Khalid University, Abha 61421, Saudi Arabia

Abstract: Recent statistics indicate that as of 2023, the global renewable energy capacity has reached new heights, with Saudi Arabia significantly contributing to this growth through its strategic initiatives. The kingdom is particularly focusing on harnessing solar power, given its abundant sunlight, and is also exploring wind energy, leveraging its vast desert landscapes. These efforts are part of Saudi Arabia’s broader strategy to become a global leader in renewable energy. This paper provides a detailed exploration of Saudi Arabia’s ambitious journey from a fossil-fuel-dominated energy sector to a more sustainable, renewable-energy-driven future. Anchored in the broader context of global energy trends, the study emphasizes the critical shift toward renewable resources, with a particular focus on Saudi Arabia’s unique position in this global movement. Key to this transition is Saudi Arabia’s Vision 2030, a strategic framework that guides the country’s renewable energy policies and initiatives. A comprehensive review of these policies, including other governmental and international collaborations that support renewable energy development, is offered. The current state of renewable energy in Saudi Arabia is assessed, including an overview of existing projects and production statistics. The paper also explores emerging technologies such as energy storage systems and smart grid solutions, emphasizing their role in Saudi Arabia’s energy transition. An impact assessment is conducted to understand the environmental, economic, and social effects of this energy shift. The paper also includes a comparative analysis of other countries’ renewable energy transitions, extracting lessons and best practices applicable to the Saudi context. Strategic recommendations and reflections on Saudi Arabia’s future role in the global energy landscape are provided for stakeholders in energy policy, environmental planning, and sustainable development.

Keywords: Saudi energy; renewable energy; sustainability; energy transition; energy policies; environmental impact

1. Introduction

In the ever-evolving landscape of global energy, the concept of smart energy has emerged as a transformative force, reshaping the way nations produce, distribute, and consume power. The global energy arena is undergoing a profound metamorphosis, driven by a pressing need for sustainability and resilience. Smart energy, at its core, represents a paradigm shift from conventional, resource-intensive practices to technologically advanced, environmentally conscious approaches. It encompasses a wide spectrum of innovations, including the integration of renewable energy sources, the implementation of digital technologies, and the promotion of energy efficiency. The urgency of this transition is underscored by mounting concerns over climate change, energy security, and resource scarcity [1,2].

Saudi Arabia, traditionally known for its vast oil reserves and dominance in the global petroleum market, is at a pivotal juncture in its energy history. The kingdom’s economy has been intrinsically linked to oil, with the sector accounting for approximately 50% of its GDP and 70% of export earnings [3]. However, this heavy reliance on fossil fuels has prompted a strategic reevaluation in the face of global environmental concerns, fluctuating oil prices, and the finite nature of fossil fuel resources. As per the global carbon budget
(GCB) and world data, the per capita CO$_2$ emissions from fossil fuels have been vastly increased since 1998 in Saudi Arabia. Figure 1 presents the per capita CO$_2$ emissions from fossil fuels by Saudi Arabia. Figure 2 presents the per capita CO$_2$ emissions in tonnes over a 100-year scale. Figure 3 presents the per capita greenhouse gas (GHG) emissions by different sectors in Saudi Arabia [4]. Figure 2 implies that the electric power generation from fossil fuels contribute the major sector for GHG emissions. The transition to renewable energy is not merely an environmental or economic imperative but a strategic necessity to ensure long-term sustainability and economic diversification.

Figure 1. Per capita tons of CO$_2$ emissions from fossil fuels of Saudi Arabia [4].

Figure 2. Greenhouse gas emissions by different sectors in Saudi Arabia [4].
The scholarly analysis of Saudi Arabia’s renewable energy policies provides a vital lens to evaluate Saudi Arabia’s strategic alignment with global renewable initiatives. Authors such as Al-Sarihi and Mansouri have highlighted Saudi Arabia’s Vision 2030 and its renewable targets. The challenges of investment climate, regulatory frameworks, and technological adaptation need robust attention for these goals to be fully realized [5]. This vision invites a comparative analysis with nations such as Germany and China, who are leaders in renewable energy implementation, to discern best practices and potential pitfalls. For instance, Lei et al. (2023) highlight how Germany’s Energiewende (energy transition) not only focuses on increasing renewable capacity but also emphasizes public participation and the phasing out of nuclear energy [6]. Similarly, China’s integrated approach, merging massive governmental support with cutting-edge technological innovation, as discussed by Zhao et. al, proposes a comparative perspective that possibly optimize Saudi Arabia’s policy frameworks [7]. By engaging with these comparative analyses, this section aims to contextualize Saudi Arabia’s renewable energy efforts within the broader global energy transition landscape, providing a multidimensional view of its policy effectiveness and areas ripe for development.

The rationale for this shift is underpinned by several key factors. Firstly, the global push toward sustainable development and the reduction of greenhouse gas emissions, as outlined in the Paris Agreement, necessitates a move away from fossil fuels [8]. Secondly, the volatility of oil prices poses significant risks to an economy heavily reliant on oil exports. Diversifying the energy mix can provide greater economic stability. Thirdly, technological advancements have made renewable energy sources such as solar and wind power more viable and cost-effective. Saudi Arabia, with its abundant sunshine and vast desert landscapes, is particularly well-positioned to capitalize on solar energy [3,9].

At the forefront of this transition is Saudi Arabia’s ambitious Vision 2030, a sweeping set of economic and social reforms aimed at reducing the kingdom’s dependence on oil, diversifying its economy, and developing public sectors such as health, education, infrastructure, recreation, and tourism [10]. A central component of Vision 2030 is the transformation of the energy sector, with a significant focus on developing renewable energy sources. The plan sets a target of generating 9.5 gigawatts of renewable energy by 2025, laying the groundwork for a more diversified and sustainable energy portfolio [9].

This paper aims to provide a comprehensive review of Saudi Arabia’s journey toward a renewable energy future as follows:

- Understand the evolution of Saudi Arabia’s energy sector from being heavily oil-dependent to recognizing the need for diversification and sustainability;
- Explore the impact of Vision 2030 on the country’s energy policies, focusing on the objectives, strategies, and targets set to increase renewable energy production;
- Examine the role of international partnerships, agreements, and memberships in global organizations in supporting Saudi Arabia’s renewable energy goals;
- Assess Saudi Arabia’s renewable energy resources, including geographical advantages, current projects, and future potential in solar and wind energy;
- Emphasize the role of technology in the energy transition, including advancements in energy storage, smart grids, and electric vehicles;
- Explore the broader implications of the transition to renewable energy, including its impact on carbon emissions, job creation, economic diversification, and public perception;

Figure 3. Timeline of Saudi Arabia’s plan for energy transition.
• Identify strategies and policy recommendations to further advance Saudi Arabia’s renewable energy initiatives and overcome challenges in the energy transition.

This paper is organized as follows. The methodology is explained in Section 2. Section 3 provides an overview of the energy transition in Saudi Arabia and the globe. The evaluation of the policy framework and initiatives is presented in Section 4. The current state of renewable energy in Saudi Arabia is reviewed and studied in Section 5. Recommendations and conclusion of this review research are provided in Section 6.

2. Methodology

This section defines the methodology employed in this comprehensive study, focusing on Saudi Arabia’s transition toward renewable energy. The approach is multi-faceted, integrating qualitative and quantitative analyses to provide a holistic understanding of the energy landscape in Saudi Arabia. The following steps outline the methodology:

• Literature review from sources including peer-reviewed academic journals, industry reports, policy documents, government publications, and press release websites;
• Policy and regulatory evaluation;
• Statistical data extraction and analysis on energy consumption, production patterns, and renewable energy projects
• Saudi Renewable energy evaluation and implications;
• Technological assessment of emerging technologies such as energy storage and smart grids, are assessed to understand their role in Saudi Arabia’s energy transition;
• The environmental, economic, and social impacts of Saudi Arabia’s shift to renewable energy;
• Formulation of the recommendations.

The following important queries are answered in the present article.

• What is the historical context of Saudi Arabia’s energy sector, particularly its reliance on fossil fuels, and how has this shaped the country’s current energy policies?
• How is Saudi Arabia’s Vision 2030 influencing the transformation of its energy sector toward renewable energy?
• How are international collaborations and agreements aiding Saudi Arabia in its renewable energy ambitions?
• What are the current state and potential of renewable energy resources in Saudi Arabia, especially solar and wind energy?
• What technological advancements and innovations are being adopted or developed in Saudi Arabia to facilitate the energy transition?
• What are the environmental, economic, and social impacts of the renewable energy transition in Saudi Arabia?
• What recommendations can be made for accelerating Saudi Arabia’s transition to a diversified and sustainable energy mix?

3. Background and Context

3.1. Saudi Energy’s Background

Saudi Arabia’s journey in the realm of energy is intertwined with its emergence as a global economic powerhouse. Saudi Arabia consistently ranks among the world’s top oil producers and exporters. It holds vast oil reserves, and its energy policies have far-reaching implications for global energy markets [11]. In 2022, Saudi Arabia held the position of the third-largest producer of crude oil and condensate globally, while also maintaining its status as the leading exporter of crude oil worldwide. Additionally, it held the distinction of being the foremost producer of crude oil within the Organization of the Petroleum Exporting Countries (OPEC) [12]. Saudi Arabia plays a significant role as a prominent member of the Organization of the Petroleum Exporting Countries Plus (OPEC+).

Saudi Arabia’s energy sector has undergone a remarkable transformation over the years, shaped by key milestones. The Kingdom’s energy story began with the discovery of oil in commercial quantities in the 1930s. This marked a turning point in its history,
catapulting Saudi Arabia into a pivotal position on the global energy stage [11]. In the 1970s, Saudi Arabia took control of its oil reserves by nationalizing the Arabian American Oil Company (Aramco). This move gave the government greater leverage in shaping energy policies and investments [13,14]. Saudi Arabia’s strategic importance as a reliable oil producer was solidified during the Gulf War in 1990–1991 when it played a significant role in stabilizing global oil markets [11]. Recognizing the need to diversify its economy, Saudi Arabia embarked on a journey to reduce its dependence on oil revenues. The Saudi Vision 2030 initiative, launched in 2016, outlines a roadmap for economic diversification and the development of other sectors [10,15]. The Vision 2030 initiatives in Saudi Arabia aim to promote the widespread utilization of renewable energy sources and the development of unassociated natural gas resources across the nation. Figure 3 presents the timeline of Saudi Arabia’s plan for energy transition. It aspires to reduce the reliance on oil- and associated natural gas-fired electricity generation in favor of renewable energy-based electricity generation. By the end of 2023, the total installed renewable energy capacity in Saudi Arabia was 2.8 GW, and the capacity of renewable energy projects under construction had exceeded 8 GW [16,17].

3.2. Global Energy Trends and the Shift toward Renewables

The global energy landscape is undergoing a significant transformation marked by a decisive shift toward renewable energy sources [18,19]. This energy shift is a multifaceted concept that encompasses a range of innovative strategies and technologies designed to optimize energy production, distribution, and consumption. It entails the intelligent integration of renewable energy sources, such as solar and wind power, into existing energy grids. Moreover, the transformation in the energy landscape leverages digital solutions, such as smart grids and advanced metering systems, to enhance energy efficiency and reliability [20,21]. This transition is driven by a confluence of factors, including technological advancements, declining costs of renewable energy technologies, growing environmental awareness, and policy initiatives aimed at mitigating climate change [8,22–24]. In recent years, renewable energy, particularly solar and wind power, has seen unprecedented growth worldwide. According to the International Renewable Energy Agency (IRENA), global renewable energy capacity will increase by 9.6% in 2022, with solar and wind energy accounting for 90% of this expansion. Figure 4 shows the global renewable energy growth trends. Additionally, other factors driving energy transformation are energy efficiency and security. Energy efficiency improvements reduce operational costs, leading to economic savings for industries and households alike [23,25]. Enhanced energy security and reduced reliance on imported fossil fuels bolster a nation’s sovereignty and resilience in the face of global energy market fluctuations [25]. For that, this trend is a clear indication of the shifting priorities in global energy policies, moving away from fossil fuels toward more sustainable and environmentally friendly sources. Figure 5 presents the global energy investment in clean energy and in fossil fuels, from 2015 to 2023. It is observed that there is a vast increase in the investment in clean energy [25,26].

The economic viability of renewables has also improved significantly. The cost of solar photovoltaic (PV) power has decreased by around 89% since 2010, making it one of the cheapest sources of energy in many parts of the world [27]. Wind energy costs have also seen a substantial reduction by about 69% for onshore wind projects and by about 39% for offshore wind projects. Moreover, the cost of concentrated solar power has declined by 69% since 2010 [28,29]. These cost reductions are transforming energy markets and making renewables increasingly competitive with traditional fossil fuels.
3.3. Saudi Arabia’s Energy Consumption and Production Patterns

Saudi Arabia’s energy sector has been predominantly characterized by its substantial oil production and consumption patterns. As the world’s largest oil exporter, the kingdom has historically focused on the exploration and exportation of crude oil. However, Saudi Arabia’s energy demand has experienced significant growth due to industrialization and population expansion. Rapid industrialization has driven up energy demand, with industries such as petrochemicals, manufacturing, and mining requiring substantial energy inputs [1,31]. In addition, a growing population contributes to increased residential energy consumption. Meeting the energy needs of a burgeoning population is a crucial consideration for energy planners [32]. The country’s electricity consumption, for instance, has been growing at an average rate of 6% per year, one of the highest rates in the world [22]. This increase in domestic energy demand has led to a greater consumption of the kingdom’s oil and gas resources, which could otherwise be exported.
According to IEA, Saudi energy production has increased by about 66% since 1990 [1,33]. The total primary energy supply has also increased by 296.26%. Figure 6 shows the Saudi electricity production by different sources [4]. Moreover, electricity consumption has increased by about 451%. The total CO₂ emission has also increased by 220%.

The current energy consumption pattern in Saudi Arabia is heavily reliant on fossil fuels, with oil and natural gas accounting for nearly all of the country’s electricity generation. Figure 7 represents Saudi Arabia’s Energy Consumption from 1985 to 2021 [4]. Energy consumption involves the energy from crude oil, oil products, natural gas, and electricity. Figure 8 shows Saudi Arabia’s electricity consumption in TJ by different sectors, from 1990 to 2020 [4]. This reliance poses several challenges, including the inefficient use of valuable export commodities, environmental concerns, and the need for a more sustainable and diversified energy mix. The rise in energy demand necessitates expanded energy production capacity. This has led to the exploration of renewable and clean energy sources to complement conventional fossil fuel-based production [9,34]. To balance energy supply and demand, Saudi Arabia is transitioning toward an energy mix that includes renewables, natural gas, and nuclear power. Recognizing these challenges, Saudi Arabia has embarked on a strategic shift toward renewable energy sources under Vision 2030.

Figure 6. Saudi electricity production by source [4].

Figure 7. Saudi Arabia’s total energy consumption [35].
The urgent need to combat climate change and address environmental concerns is a primary driver of the energy transition. Rising global temperatures, extreme weather events, and the depletion of natural resources have galvanized international efforts to reduce carbon emissions [36,37]. Figure 9 depicts the comparison of the carbon intensity of electricity by Saudi Arabia and the world [4]. The carbon intensity of Saudi Arabia is much higher compared to the world’s carbon intensity. The Paris Agreement, adopted in 2015, stands as a landmark commitment by nations to limit global warming [8]. For that, the environmental and economic imperatives for transitioning to renewable energy in Saudi Arabia are compelling [38,39]. Environmentally, the shift is crucial in reducing greenhouse gas emissions and combating climate change. Saudi Arabia, as one of the top oil-producing countries, has a significant carbon footprint. Transitioning to renewable energy sources such as solar and wind can substantially reduce carbon emissions, contributing to global efforts to mitigate climate change. Moreover, the kingdom’s geographical location, characterized by high solar irradiance and vast desert areas, presents an ideal setting for large-scale solar energy projects.

The energy transition presents significant economic opportunities, including job creation, new markets, and innovation [12,40]. The diversification into renewable energy
aligns with Saudi Arabia’s strategic objectives to reduce its dependence on oil revenues and develop a more sustainable and diversified economy [2]. Investing in renewable energy not only opens new avenues for economic growth but also creates job opportunities, stimulates technological innovation, and attracts foreign investment. Additionally, reducing domestic consumption of oil and gas allows for more of these resources to be available for export, thereby maximizing revenue from fossil fuel resources.

The economic benefits of renewable energy are further enhanced by the declining costs of renewable technologies, making them increasingly competitive with traditional energy sources. This cost-effectiveness, combined with environmental benefits, positions renewable energy as a key pillar in Saudi Arabia’s future economic and environmental strategy.

4. Policy Framework and Initiatives

4.1. Detailed Analysis of Vision 2030

Government policies and regulations play a pivotal role in steering the energy transition. Incentives, subsidies, carbon pricing mechanisms, and renewable energy targets influence investment decisions and market dynamics [41,42]. As the global energy sector undergoes a seismic shift, driven by environmental imperatives, technological advancements, and economic opportunities, Saudi Arabia positions itself to harness these global trends [23,27,33,43]. The Kingdom’s vision for smart energy aligns with these driving forces, underscoring the significance of its transition.

Vision 2030, launched in 2016, represents a pivotal framework in Saudi Arabia’s strategic planning, aiming to diversify the economy and reduce dependence on oil revenues [8,10]. This ambitious plan encompasses various sectors, but its implications for the energy sector are particularly significant. The Vision outlines objectives to increase the share of renewable energy in the total energy mix, aiming to reach 27.3 GW of renewable energy capacity by 2023 and 58.7 GW by 2030, with solar energy expected to account for the majority of this capacity [10,34].

The Vision 2030 framework also emphasizes the development of a sustainable energy sector that can meet the growing domestic energy demand while preserving natural resources for future generations. It includes initiatives to promote energy efficiency and reduce carbon emissions, aligning with global climate change mitigation efforts. The plan further envisages the creation of a dynamic renewable energy market in Saudi Arabia, encouraging private-sector participation and international investment [25].

One of the key components of Vision 2030 is the National Renewable Energy Program (NREP), which is designed to support the development of renewable energy projects across the kingdom [44]. The NREP aims to not only increase renewable energy capacity but also to localize the renewable energy value chain, fostering domestic industries and job creation in the sector.

4.2. Governmental Commitment to Renewable Energy

In addition to Vision 2030, Saudi Arabia has implemented several policies and initiatives to support the growth of renewable energy. Figure 10 presents the efforts toward Vision 2030 for renewable energy by Saudi Arabia.

The National Renewable Energy Program (NREP) and National Transformation Program (NTP), through the Ministry of Energy, Industry, and Mineral Resources, have devised a roadmap for promoting and deploying renewable energy transformation to meet future electricity demand in Saudi Arabia [45]. Moreover, the Renewable Energy Project Development Office (REPDO) is another key initiative, tasked with executing the renewable energy program under Vision 2030 [2,46]. REPDO plays a critical role in tendering processes for renewable energy projects, ensuring transparency and competitiveness in the sector [9]. Another initiative through the Ministry of Energy is the Saudi Energy Efficiency Program (SEEP) which focuses on improving energy efficiency across various sectors, including industrial, transport, and building sectors. This program is crucial in reducing the overall energy demand, thereby allowing a greater proportion of energy consumption to be met by
renewable sources [47]. The mentioned initiatives and programs have introduced financial incentives and regulatory reforms to attract investments in renewable energy. These include feed-in tariffs, subsidies, and tax incentives for renewable energy projects [48]. Furthermore, the Saudi Electricity Company (SEC) has been actively involved in integrating renewable energy into the national grid, ensuring grid stability and reliability as the share of renewables increases [49]. It also plays a crucial role in helping the Kingdom and the region achieve energy efficiency and Net Zero emissions by 2060.

Figure 10. Efforts toward vision 2030 for renewable energy by Saudi Arabia.

Furthermore, the King Salman Renewable Energy Initiative, which was introduced in 2018, seeks to enhance the proportion of renewable energy within the energy composition of Saudi Arabia [9,50]. Moreover, the Saudi Green Initiative was unveiled in March 2021 [51]. It is a comprehensive endeavor designed to mitigate carbon emissions and address the global challenge of climate change. The program encompasses a range of objectives, including the ambitious target of afforesting Saudi Arabia with 10 billion trees, achieving a substantial 60% reduction in carbon emissions within the region, and augmenting the proportion of renewable energy sources in the energy portfolio.

In addition, the Public Investment Fund (PIF) of Saudi Arabia has made substantial investments in renewable energy enterprises on a global scale. As an illustration, the Public Investment Fund (PIF) has made investments in ACWA Power, a company engaged in the global development of renewable energy projects, including those in Saudi Arabia [52].

4.3. International Collaborations and Agreements

Saudi Arabia’s renewable energy ambitions are further bolstered by its active participation in international collaborations and agreements. Figure 11 displays Saudi Arabia’s international collaborations and agreements in renewable energy. Saudi Arabia’s commitment to renewable energy is underscored by its Vision 2030 and participation in global agreements. Saudi Arabia, as a member of the G20 and a signatory of the Paris Agreement, is aligning its energy policies with global climate objectives [8,53]. This signifies the
country’s commitment to mitigating climate change. The Energy Transition and Climate Sustainability Working Group was established by Saudi Arabia, the host of the G20 meeting in 2020. The primary objective of the organization is to advance the cause of a sustainable energy transition and effectively tackle the issue of climate change by fostering collaboration among member nations of the G20. Saudi Arabia is also a member of the International Renewable Energy Agency (IRENA), through which it engages in global dialogues and knowledge exchange on renewable energy technologies and policies [23].


5.1. Renewable Resources Availability

Saudi Arabia boasts abundant renewable resources, particularly in wind and solar energy. The geographical location provides exceptional solar irradiance levels, with an annual average of approximately 2500 kWh/m² [55]. The country’s vast desert areas are ideal for solar energy installations. The Kingdom has also substantial wind energy potential, particularly in regions such as the Empty Quarter (Rub’ al Khali) and along the Red Sea coast. Wind
speeds in some areas can reach an average of 7–9 m per second [56]. Figure 13a,b illustrates the geographical distribution of wind energy potential across Saudi Arabia. These visual representations showcase the variation in renewable resources across the country.

**Figure 12.** Solar energy potential map of Saudi Arabia [56].

**Figure 13.** Wind energy potential map of Saudi Arabia. (a) Wind speed, (b) mean wind power density at 100 m [57].
5.2. Overview of Renewable Energy Projects

Saudi Vision 2030 outlines a clear roadmap for the integration of renewables to generate 50% of the country’s electricity from renewables by 2030 [10,15,44]. Saudi Arabia has embarked on several ambitious renewable energy projects, including the NEOM Line, wind farms, and photovoltaic (PV) plants [58,59]. These projects contribute significantly to the country’s renewable energy targets. The proposed objective encompasses an approximate capacity of 40 GW derived from solar energy, 16 GW generated from wind energy, and 2.7 GW harnessed from various other renewable sources. The emphasis on renewable energy in Saudi Arabia is seen through its implementation of extensive solar projects. Table 1 shows the Saudi’s renewable projects and their operation status [11].

In June 2021, the Sakaka solar project commenced its operations, signifying a noteworthy achievement as the first large-scale solar power endeavor in Saudi Arabia [60]. Another example of a noteworthy endeavor within the nation is the Sudair solar project, boasting a substantial capacity of 1.5 GW [61]. Furthermore, Saudi Arabia is currently engaged in wind power initiatives as part of its efforts to broaden its renewable energy portfolio. The Dumat Al Jandal wind project, which is considered the inaugural utility-scale wind farm in the country, is anticipated to possess a planned capacity of 400 MW [62]. Additionally, PIF is committed to renewable energy projects through its associated companies. A PIF tourism company, The Red Sea Development Company, has also announced plans to power its entire tourism project with renewable energy, primarily solar and wind, showcasing a commitment to sustainable development [63,64]. Figure 14 shows the spread of renewable energy projects by 2030 in Saudi Arabia. The aforementioned facts serve to underscore Saudi Arabia’s dedication to the transformation of its energy sector to achieve a more sustainable and technologically advanced future.

Table 1. Saudi Arabia’s renewable energy projects [11,65].

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Type</th>
<th>Capacity (MW)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sudair</td>
<td>Solar</td>
<td>1500</td>
<td>Under construction</td>
</tr>
<tr>
<td>Rass</td>
<td>Solar</td>
<td>700</td>
<td>Under construction</td>
</tr>
<tr>
<td>Al-Shuaiba</td>
<td>Solar</td>
<td>600</td>
<td>In Operation</td>
</tr>
<tr>
<td>Dumat Al-Jandal</td>
<td>Wind</td>
<td>400</td>
<td>In Operation</td>
</tr>
<tr>
<td>Jedda</td>
<td>Solar</td>
<td>300</td>
<td>Under construction</td>
</tr>
<tr>
<td>Rabigh</td>
<td>Solar</td>
<td>300</td>
<td>In Operation</td>
</tr>
<tr>
<td>Saad</td>
<td>Solar</td>
<td>300</td>
<td>Under construction</td>
</tr>
<tr>
<td>Sakakah</td>
<td>Solar</td>
<td>300</td>
<td>In Operation</td>
</tr>
<tr>
<td>Qurayyat</td>
<td>Solar</td>
<td>200</td>
<td>Under construction</td>
</tr>
<tr>
<td>Wadi ad-Dawasir</td>
<td>Solar</td>
<td>120</td>
<td>Under construction</td>
</tr>
<tr>
<td>Layla</td>
<td>Solar</td>
<td>80</td>
<td>Under construction</td>
</tr>
<tr>
<td>Medina</td>
<td>Solar</td>
<td>50</td>
<td>Under construction</td>
</tr>
<tr>
<td>Rafha</td>
<td>Solar</td>
<td>20</td>
<td>Under construction</td>
</tr>
<tr>
<td>Al-Shuaibah 2</td>
<td>Solar</td>
<td>2060</td>
<td>Announced</td>
</tr>
<tr>
<td>Rass 2</td>
<td>Solar</td>
<td>2000</td>
<td>Announced</td>
</tr>
<tr>
<td>Al-Kahfa</td>
<td>Solar</td>
<td>1425</td>
<td>Announced</td>
</tr>
<tr>
<td>Saad 2</td>
<td>Solar</td>
<td>1125</td>
<td>Announced</td>
</tr>
<tr>
<td>Al-Henekiyah</td>
<td>Solar</td>
<td>1100</td>
<td>Announced</td>
</tr>
<tr>
<td>Yanbu</td>
<td>Wind</td>
<td>700</td>
<td>Announced</td>
</tr>
<tr>
<td>Al-Ghat</td>
<td>Wind</td>
<td>600</td>
<td>Announced</td>
</tr>
<tr>
<td>Waad Al-Shamal</td>
<td>Wind</td>
<td>500</td>
<td>Announced</td>
</tr>
<tr>
<td>Tubarjal</td>
<td>Solar</td>
<td>400</td>
<td>Announced</td>
</tr>
</tbody>
</table>
5.3. Energy Technological Advancements and Innovations

Saudi Arabia is making notable progress in its transition toward a more sustainable and technologically advanced energy system through the adoption of a variety of renewable energy sources, the implementation of energy efficiency measures, and the promotion of electric vehicles [66]. Emerging technologies such as energy storage and smart grids are pivotal in the integration of renewable energy into Saudi Arabia’s energy system [20,67,68]. Energy storage, particularly battery storage systems, has become increasingly important to manage the intermittent nature of solar and wind energy. According to Javadi et al., the implementation of large-scale battery storage solutions can significantly mitigate the variability of renewable energy and can be a key enabler for increasing the penetration of renewables into the national grid [69]. Saudi Arabia is exploring large-scale battery storage solutions to stabilize the grid and ensure a consistent energy supply.

Saudi Arabia has made substantial investments in smart grid technologies, specifically focusing on advanced metering infrastructure (AMI) and smart meters [70]. The country has set a target to deploy over 10 million smart meters by 2025, with the objective of enhancing the monitoring and control of energy usage. Moreover, Saudi Arabia represented in SEEC is now undertaking energy efficiency measures to enhance the utilization of energy resources and mitigate wasteful practices. The Saudi Energy Efficiency Program for Air Conditioning (SEEP-AC) has set a target of achieving a 30% enhancement in energy efficiency for air conditioning systems [71]. This initiative has the potential to conserve up to 7 GW of electricity by the year 2030.

Smart grids, equipped with advanced communication and control technologies, are another area of focus. These grids enable better demand management, reduce transmission losses, and improve overall energy efficiency. The Saudi Electricity Company has initiated several smart grid projects aiming to modernize the electricity infrastructure and support the integration of renewable energy sources [72].

In the year 2020, the electricity consumption associated with water desalination in Saudi Arabia accounted for 6% of the total energy usage [73]. There has been a significant growth in the production of desalinated water. The Saline Water Conversion Corporation (SWCC) in Saudi Arabia is now involved in efforts to improve multiple desalination plants in order to achieve a decrease in their energy consumption [74].

Additionally, Saudi Arabia is aggressively advocating for the widespread adoption of electric vehicles (EVs) as a means to decrease reliance on transportation fueled by fossil
5.4. Role of Innovation in Energy Transition

Innovation plays a critical role in Saudi Arabia’s energy transition. The kingdom is not only adopting existing technologies but also investing in research and development (R&D) to innovate new solutions tailored to its unique environmental and economic context [5]. Initiatives such as the King Abdullah City for Atomic and Renewable Energy (KACARE) and King Abdullah Petroleum Studies and Research Center (KAPSARC) are at the forefront of this innovation drive, focusing on developing new renewable energy technologies and enhancing existing ones [77,78]. Collaborations with international research institutions and private sector partnerships are also crucial in fostering innovation. These collaborations have led to breakthroughs in areas such as solar panel efficiency, wind turbine design, and energy storage solutions, all of which are essential for a successful energy transition in Saudi Arabia.

5.5. Impact Assessment of Energy Transition

The transition to renewable energy in Saudi Arabia has significant environmental implications, particularly in reducing carbon emissions. The kingdom, historically a large emitter due to its reliance on fossil fuels, has the potential to significantly lower its carbon footprint through renewable energy initiatives. According to a report by the Saudi Ministry of Environment, Water and Agriculture, the implementation of solar and wind projects under Vision 2030 could reduce carbon emissions by up to 35% by 2030 [51,79]. Additionally, the shift toward renewables is expected to reduce air pollution and conserve water resources, as these technologies require less water for operation compared to fossil fuel-based power generation [47,79].

The economic impact of Saudi Arabia’s renewable energy transition is multifaceted, encompassing job creation and industry growth. The renewable energy sector is poised to create a significant number of jobs, particularly in the fields of solar and wind energy. A study by the Saudi Ministry of Economy and Planning suggests that the renewable energy sector could generate over 100,000 jobs by 2030 [40,80]. This transition is also expected to stimulate growth in related industries, such as manufacturing, construction, and maintenance services. Furthermore, the diversification of the economy away from oil dependence is likely to enhance economic stability and attract foreign investment [81].

The social impacts of renewable energy adoption in Saudi Arabia are significant, encompassing changes in public perception and lifestyle. The increasing awareness and acceptance of renewable energy among the Saudi population are evident, with a survey conducted by the King Abdulaziz City for Science and Technology showing that over 70% of respondents favor renewable energy over traditional fossil fuels [14,81]. This shift in public perception is crucial for the adoption of renewable energy technologies and sustainable lifestyle practices. Additionally, the integration of renewable energy into the national grid is expected to lead to changes in energy consumption patterns and encourage energy-saving behaviors among the populace [82].

6. Recommendations and Conclusions

6.1. Recommendations

Saudi Arabia is on the right track in the deployment of renewable energy technologies, such as solar and wind power. However, this can be accelerated and achieved by increasing the capacity of existing projects and initiating new ones. Saudi Arabia should consider implementing policies that incentivize renewable energy investments, such as tax credits...
or subsidies. Streamlining regulatory processes can facilitate quicker implementation of renewable projects.

Moreover, efforts to reduce energy consumption and improve energy efficiency should be a top priority. Implementing energy-efficient technologies and practices in industrial, commercial, and residential sectors can lead to substantial energy savings. The government should promote energy efficiency through incentives and mandatory standards.

In addition, Saudi Arabia should continue diversifying its energy sources to enhance energy security. This includes expanding its nuclear energy program, exploring geothermal resources, and investing in energy storage technologies. A diversified energy mix will reduce dependence on a single energy source and increase resilience to supply disruptions.

Substantial investment in Research and Development (R&D) is also pivotal for unlocking innovative solutions that could substantially reduce the cost and enhance the efficiency of renewable energy technologies. The government, in collaboration with the private sector, should invest in R&D initiatives aimed at overcoming technical and logistical hurdles synonymous with renewable energy adoption [48]. Moreover, fostering a thriving startup ecosystem could help in nurturing innovative solutions tailored to Saudi’s unique context.

Finally, public awareness and education are instrumental in expediting the adoption of smart energy solutions. To effectively enhance the adoption of renewable energy sources among the Saudi population, an inclusive public awareness campaign is essential. This initiative should focus on educating citizens about the unswerving benefits of renewable energy, particularly in terms of reducing CO₂ emissions and combating climate change, which is critical for ensuring a sustainable future for the Kingdom. Incorporating renewable energy subjects into academic curriculums and university courses can cultivate a generation of skilled in sustainable practices. This educational approach will empower citizens to make knowledgeable decisions about energy use, thereby aligning public behavior with the national goals of reducing CO₂ emissions and transitioning to a renewable energy-based economy. Concerted efforts should be made to educate the public on the benefits and the imperatives of transitioning to smart energy systems. Additionally, integrating renewable energy and sustainability courses in academic curricula could also be instrumental in cultivating a culture of energy conservation.

6.2. Conclusions

This paper comprehensively explored Saudi Arabia’s journey toward renewable energy, highlighting the global energy trends, policy frameworks, the current state of renewable energy, technological advancements, challenges, and impact assessments.

Saudi Arabia’s journey toward smart energy and renewable resources is of paramount significance for the nation’s sustainable development and global energy transformation. The adoption of renewable energy sources not only conserves valuable resources but also contributes to environmental preservation, economic diversification, and enhanced energy security.

Looking ahead, Saudi Arabia’s future in renewable energy appears promising. The Vision 2030 initiative has set ambitious goals for renewable energy capacity, signaling the kingdom’s commitment to a green and prosperous future. Through strategic planning, continued investments, and international collaborations, Saudi Arabia is poised to become a leader in the global shift toward smart energy. The recommendations outlined in this paper provide a roadmap for the kingdom to achieve its energy goals and strengthen its position in the evolving energy landscape.

As Saudi Arabia forges ahead with its energy initiatives, it not only secures its own energy future but also contributes to the global effort to combat climate change and build a sustainable world for generations to come.

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