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Energy Transition in Saudi Arabia: Harnessing Solar Solutions for a Sustainable Future Renewable Energy Blend While Navigating Challenges and Capitalizing on Opportunities

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Abstract

Saudi Arabia's transition towards renewable energy is crucial in reducing its historical dependency on fossil fuels, motivated by the urgent need to combat global warming and diversify its energy portfolio. This study critically examines the role of solar energy, positioned as a primary renewable resource under the ambit of Saudi Vision 2030. By reviewing a comprehensive body of literature spanning the past 50 years using the PRISMA framework, the research aims to assess the feasibility of solar energy within the nation's renewable landscape. A systematic analysis of 292 publications, narrowing down to 72 selected articles through rigorous quality assessment and bibliometric analysis, reveals substantial opportunities for enhancing solar energy efficiency. The findings underscore the potential of advanced solutions such as perovskite and quantum dot solar cells, alongside the implementation of anti-soiling coatings and innovative cooling mechanisms. Localizing manufacturing capabilities and increasing private sector engagement emerge as critical components for fostering solar energy adoption. Additionally, techno-economic assessments indicate that a pivot to solar power could offer significant environmental advantages, characterized by reduced installation and maintenance costs. Nonetheless, entrenched fossil fuel subsidies and prevailing pricing frameworks present significant barriers to the integration of renewable energy. The adoption of solar energy carries far-reaching implications for Saudi Arabia, likely resulting in improved environmental quality and diminished greenhouse gas emissions. This study advocates for essential policy reforms and the establishment of transparent feed-in tariff mechanisms to facilitate the realization of the Kingdom's renewable energy objectives. Future research directions should delve into the intricate techno-economic relationships between renewable energy development, economic growth, and environmental sustainability as Saudi Arabia progresses in its energy transition.

Index-words: *Localized fabrication, Perovskites and quantum dot solar cells, Renewable energy transition, Policy reforms in Saudi Arabia, Techno-economic evaluation.*

I. Introduction

The Kingdom of Saudi Arabia (KSA) possesses the second-largest confirmed crude oil reserves globally, surpassed only by Venezuela. In addition to its substantial reserves, Saudi Arabia ranks among the largest producers of oil, achieving a record production level of 10.3 million barrels per day in March 2015 [1]. However, the combustion of fossil fuels for energy generation is a significant contributor to greenhouse gas (GHG) emissions, which are a primary driver of global warming. In response to these environmental challenges, the Saudi government has introduced the Saudi Vision 2030 initiative, which includes strategies aimed at reducing crude oil consumption within the kingdom [2].

The overarching goals of Vision 2030 include diminishing the nation's carbon footprint and decreasing its reliance on crude oil by promoting the use of renewable energy sources to meet the rising energy demand. A key component of this vision is the National Renewable Energy Program (NREP), which represents a balanced and versatile approach to enhancing the renewable energy landscape within Saudi Arabia. The NREP is designed to adapt the local energy mix and provide long-term economic benefits for the nation while significantly increasing the contribution of renewable energy to the overall energy production.

Vision 2030 targets the generation of 54 GW by 2040, and to facilitate these targets, Saudi Arabia has initiated the development of several strategic renewable energy projects, including a 300 megawatt (MW) solar photovoltaic plant in Sakaka and two 2,400 MW wind energy facilities in Midyan and Dumat Al-Jandal, respectively [3]. Additionally, tenders are anticipated in the coming years to achieve the envisioned power capacity, creating opportunities for partnerships with the private sector in Saudi Arabia. This collaborative approach is expected to accelerate the substantial implementation of renewable energy projects.

Several studies have been done in the past that have examined Saudi Arabia's renewable energy potential and challenges. Al Zohbi and AlAmri highlighted abundant resources like solar and wind but noted reliance on fossil fuels, with barriers such as climate, low awareness, and low fossil fuel costs, requiring policy reforms and R&D [4]. Researchers have emphasized the need for renewable development despite large oil reserves, advocating for international cooperation and sustainability [5]. Aldhubaib recently reported policy efforts to reduce fossil fuel dependence, improve efficiency, and lower emissions, with recommendations for tariff reforms and support for low-income groups [6]. More recently, Zubair focused on deploying photovoltaic systems in agriculture to address water scarcity and unemployment, demonstrating economic feasibility through simulations but limited to small-scale applications. Overall, Saudi Arabia is shifting towards renewables, but faces technical, economic, and policy challenges [7].

Building upon prior research, this study offers a macro-level analysis of solar energy's strategic role in Saudi Arabia's Vision 2030, emphasizing national potential, economic viability, and policy frameworks. Unlike Zubair's micro-level focus, it provides a comprehensive assessment of technological, economic, and policy dimensions shaping the country's energy transition. In a recent study, Benhacene and Hussain reported that wind and hydropower may support Saudi Arabia's sustainability; however, they concluded that a diversified renewable mix is more aligned with Vision 2030, emphasizing solar energy for sustainable development [8].

This study critically examines barriers such as fossil fuel subsidies and pricing structures, proposing forward-looking policy reforms including feed-in tariffs and local manufacturing strategies that integrate economic, environmental, and policy perspectives. Unlike prior research, it provides a comprehensive techno-economic analysis and emphasizes the integration of solar with other renewables and technological innovations. By highlighting policy revision, technological advancements, and private sector engagement, it offers a nuanced, pragmatic pathway for Saudi Arabia's energy transition aligned with its broader economic and environmental objectives.

This study provides a unique and significant contribution to the understanding of renewable energy transformation, focusing specifically on Saudi Arabia's transition from conventional to renewable energy sources within the framework of Vision 2030. It stands out from previous research by prioritizing solar energy as a leading renewable source and conducting an in-depth analysis of the specific challenges and barriers the Kingdom encounters in this shift. This research highlights Saudi Arabia's unique socio-political and economic factors influencing solar adoption, identifies policy gaps, and suggests tailored solutions like feed-in tariffs. Globally, it underscores solar energy's role in diversifying fossil fuel-dependent nations, enriching the renewable energy discourse, and informing context-specific strategies for energy transition worldwide.

This study tests the hypothesis that the implementation of solar energy technology in the desert regions of Saudi Arabia can significantly enhance the country's energy autonomy while providing a viable alternative to conventional fossil fuels. Through a comprehensive literature review, this research identifies key challenges associated with solar energy deployment, such as installation and operational hurdles, and proposes solutions aimed at optimizing renewable energy integration. The findings underscore the considerable potential of solar energy to address the kingdom's escalating energy demands effectively. Moreover, this investigation sets a foundation for future research by emphasizing the importance of examining techno-economic factors, cost-benefit analyses, and the intricate interplay between renewable energy consumption and sustainable economic growth. Ultimately, the contributions of this study aim to inform strategic pathways for a successful energy transition, supporting Saudi Arabia's initiatives for sustainable development and the reduction of carbon emissions.

The present study is an attempt to provide a unique focus on Saudi Arabia's transition to renewable energy within Vision 2030, emphasizing solar energy as a key contributor. The following are the key contributions of the present study:

- Highlights the socio-political and economic factors influencing solar adoption, offering culturally and contextually relevant insights.
- Identifies policy gaps and proposes targeted recommendations, such as feed-in-tariff policies, to enhance regulatory effectiveness.
- Addresses challenges specific to desert regions, emphasizing the techno-economic feasibility and operational hurdles of solar deployment.
- Contributes to global understanding of renewable energy transition in fossil fuel-dependent countries, emphasizing solar's potential role.
- Explores socioeconomic and environmental implications of shifting towards solar energy, enriching existing literature.
- Sets a foundation for future research on techno-economic factors, cost-benefit analyses, and sustainable economic growth linked to renewable energy.
- Synthesizes global trends with national conditions, offering a comprehensive strategic outlook aligned with Vision 2030.
- Bridges resource potential with practical implementation through integrated economic, environmental, and policy analyses.
- Positions solar energy as a cornerstone for Saudi Arabia's long-term sustainability, economic diversification, and carbon reduction goals.

II. *Methodology*

A comprehensive literature review was conducted to systematically catalogue existing information and enhance the interpretation of the data. This manuscript is based on a systematic review guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which aims to generate evidence regarding the design and implementation of solar energy within the nation's energy strategy. The review follows the extended PRISMA guidelines as outlined by Sarkis-Onofre and colleagues [9]. The methodology is visually summarized in the PRISMA flowchart (Fig. 1).

The review process is organized into four key stages. First, relevant documents were identified from selected databases using specific search criteria and a list of pertinent keywords. Second, data collection was conducted following a clearly defined search strategy. In the third stage, a screening process was applied using predetermined inclusion and exclusion criteria. Finally, the literature selected from the filtered database consisted of articles that contained relevant information, thereby providing a robust foundation for analysis and discussion.

A. *Review process*

This study draws from two principal streams of literature. The first pertains to the potential of solar energy, considering factors such as location, available infrastructure, resources, and policies that influence the pace of implementation. The second examines various solutions implemented globally to address similar challenges. An extensive literature review was conducted on articles published in the domain of renewable solar energy and related fields.

1. Source of information

The information sources included five databases: *Scopus, Web of Science (WoS), EBSCO, DOAJ, and Science Direct.* These databases are significant as they contain extensive collections of abstracts and citations from peer-reviewed research. A systematic review process was employed to ensure the reliability and conciseness of the information. Initially, 292 journal publications were identified. Subsequently, 72 of the most relevant works were

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selected based on criteria related to geographic region, implementation challenges, and success in implementation. This study specifically focuses on the utilization of solar energy in the region, as illustrated in Fig. 1.

2. Data collection and search strategy

Initial searches were conducted up to December 31, 2024, encompassing publications from 1965 through that date. The searches utilized Scopus, Web of Science, EBSCO, DOAJ, and Science Direct, without restrictions on publication date. The search keywords were carefully selected to identify various evaluations of renewable and solar energy relevant to the study's objectives. The focus was on evaluation tools that could identify techno-economic analysis variables, implementation methodologies, and policies related to renewable energy. Consequently, the evaluation of the efficiency or effectiveness of a source was excluded, as it did not align with the study's focus. Relevant studies were identified through Boolean operators using keywords such as "renewable energy" AND ("solar" OR "photovoltaic" OR "techno-economic analysis" OR "energy transition") AND ("feasibility"), with a concentration on recent developments in solar energy implementation.

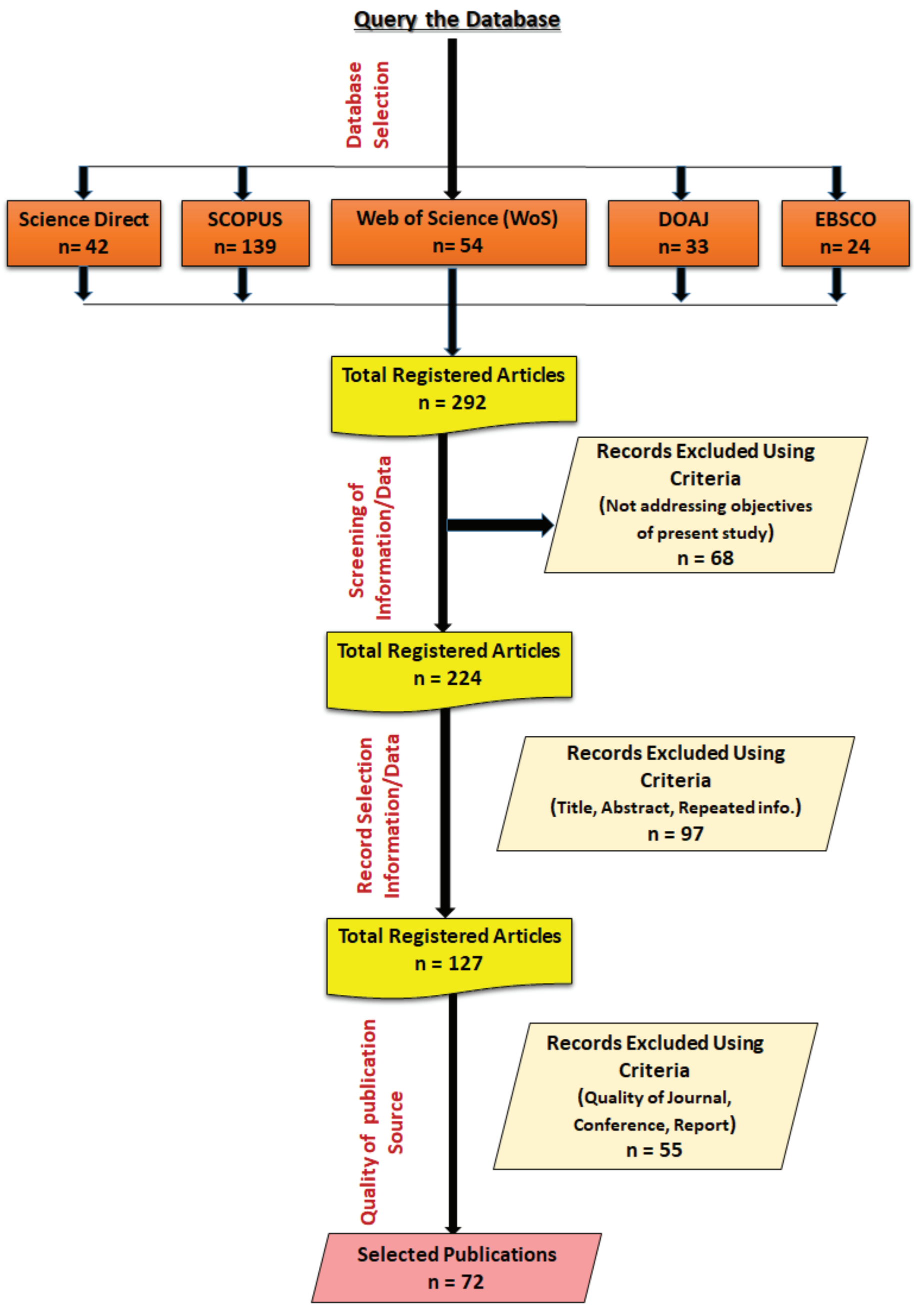

Figure 1: PRISMA flowchart for the selection of the most relevant data/information.

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3. Types of studies

Only peer-reviewed articles were selected for inclusion due to their higher quality. The focus encompassed case studies, reviews, and research addressing the feasibility of implementing solar energy alongside other renewable sources. Additionally, articles exploring policies that pertain to solar energy implementation, such as feed-in tariffs and economic feasibility, were considered. This category included discussions on innovative photovoltaic materials, cost, and design life, as well as environmental sustainability linked to renewable energy, particularly solar energy. A language restriction was applied, limiting the inclusion to articles published in English.

4. Inclusion and exclusion criteria

The systematic review included studies that described the implementation of solar energy as part of a renewable energy mix and those related to methodological evaluations of models incorporating variables of material, technology, and cost. Inclusion and exclusion criteria were established to determine which articles would be incorporated in the systematic review.

The following inclusion and exclusion criteria were utilized to extract the most relevant articles:

Inclusion Criteria

This review considered manuscripts that explicitly addressed the following topics related to renewable energy:

- Feasibility studies of renewable energy sources, specifically focusing on solar energy as part of a broader renewable energy mix.
- Methodologies for transitioning from fossil fuels to renewable energy.
- Policy evaluations pertaining to renewable energy integration or environmental impacts associated with solar energy technologies.
- Techno-economic analyses of solar energy systems, including but not limited to solar photovoltaic (PV) systems, perovskite solar cells, and quantum dot solar cells.
- Assessments of raw material production, greenhouse gas (GHG) emissions, and strategies for global warming mitigation.

Additionally, manuscripts that explore aspects of environmental sustainability related to solar energy were included. Only peer-reviewed articles published in English were considered suitable for this review.

Exclusion Criteria

Articles were excluded from the review if they fulfilled one or more of the following criteria:

- Focused solely on the analysis of impacts rather than evaluation studies.
- Discussed the historical evolution of renewable energy policy.
- Evaluated public policy reforms related to renewable energy.
- Were document types such as monographs, commentaries, theses, dissertations, or protocols.
- Addressed topics not aligned with the objectives of this study, such as politics or solar energy implementation.
- Were studies that did not evaluate the implementation of solar energy.
- Centred exclusively on planning methodologies.
- Limited their analysis to variables or natural resources without assessing policy implications.
- Evaluated other public policies unrelated to renewable energy.
- Included discussions of ecosystem services and sustainability within renewable energy policies without conducting a policy evaluation.

To mitigate potential information bias, this review was conducted as an exploratory literature review, employing relevant databases and resources to locate pertinent publications while carefully avoiding data duplication.

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III. Global perspective of renewable energy

Unlike conventional sources of energy utilised in everyday lives, such as crude oil, natural gas, and coal, renewable energy sources are sustainable. According to the Australian Renewable Energy Agency (ARENA), 'Renewable energy is produced using natural resources that are constantly replaced and never run out'. Renewable energy sources include, but are in no way or form limited to, wind, hydro, geothermal, tidal, wave, biofuel, and solar energy [10].

Among different forms of sustainable energy, biofuels are the most widely used, as shown in the comparison of global renewable energy consumption presented in Fig. 2. This is mostly due to the ease of use associated with them; firewood can be simply gathered and burned to provide warmth and cook food. More modern iterations of biofuels include bioethanol, biodiesel, biogas, syngas and biochar [11].

Wind power has ancient roots, and it has been used for navigation and agriculture since the 17th century BC by the Babylonians [12], with the first windmills in Egypt in the 1st century AD. Global renewable energy consumption rose 1.5% in 2020, with significant wind and solar capacity added [13]. Technological advances have made wind energy cost-effective, with countries like Denmark, Germany, and the US investing heavily [14], [15], supporting energy security, economic growth, and low emissions [16]. Continued research and policy support promise a sustainable future for wind power as a key renewable resource [17], [18].

Naik and colleagues conducted a study on biomass as a renewable biofuel, evaluating its physical and chemical characteristics through various analytical techniques such as XRD, TCA, ICP-MS, CHNSO, FI-IR, and FT-NIR. The results indicated that pinewood, wheat, and flax are promising candidates for biofuel production, offering minimal greenhouse gas (GHG) emissions. Furthering this exploration, a feasibility study confirmed the techno-economic viability of utilizing biomass as a renewable energy source [19]. It indicated that the GHG emissions associated with biomass-based ethanol production and use are lower than those from coal-fired electricity generation. Additionally, this study highlighted the significant socioeconomic benefits of producing bioenergy from agricultural biomass, including job creation, enhanced farmer incomes, and improved local economies [20]. Researchers used synthetic biology to engineer metabolic pathways, enhancing lignocellulosic biomass for biofuel production, focusing on low-cost pre-treatment and techniques to reduce environmental emissions [21].

Hydropower has also been utilised for quite a while, with the aid of watermills at farmhouses near rivers, and more recently using dams to generate electricity. Geothermal energy has been harnessed from the beginning through the hot springs and geysers found naturally in areas of volcanic activity. As reported earlier [22]. Turkey's hydropower, the second-largest domestic energy source, has 172 plants with 13,700 MW capacity, producing 48 TWh annually (35% of viable potential). An additional 148 plants under construction will add 8,600 MW and 20 TWh, covering 14% of the potential. [23]. Hydropower is the principal source of electricity in South and Central America, where over half of the power is generated from hydropower [24].

A recent study indicates that Indonesia's total renewable energy potential is about 419 GW, including 75 GW from hydro. Currently, hydroelectric capacity is approximately 6,602 MW, covering large, micro, and mini-hydro, representing roughly 6.5% of the region's hydro potential. [25]. However, global investment data on renewable energy presented in Table 1 shows that from the several renewable energy sources that are known, solar energy is perhaps the most popular [11], [26].

Table 1: Comparison of global investment in renewable energy technologies [11], [26]

Type of Renewable Energy	Global capital investment in renewable energy ($ Billion)						
	2008	2010	2012	2014	2016	2018	2020
Solar	52	110	140	145	125	120	140
Wind	88	110	85	120	120	122	130
Biofuel (liquid)	25	20	18	16	15	12	10

A recent study examines the impact of renewable energy systems' performance on their adaptation from 1979 to 2024. The study highlighted the need for international collaboration, especially between developed countries, and emphasized the importance of funding and sustainability indicators. The study calls for ongoing innovation and interdisciplinary cooperation to promote a sustainable energy future [27]. The International Renewable Energy Agency emphasizes that renewable energy should make up two-thirds of the global energy supply by 2050 [28]. The growing focus on renewable energy development has garnered significant attention in recent years. As a result, promoting the use of renewable resources has emerged as a shared goal and coordinated effort among nations worldwide [29].

At present, researchers are exploring a variety of methods and sources for generating renewable clean energy, including the use of natural algae to produce clean hydrogen fuel [30]. Techniques such as photochemical, thermochemical, and electrochemical processes are being employed for hydrogen production [31]. Additionally, advancements in artificial photosynthesis are contributing to clean fuel production [32].

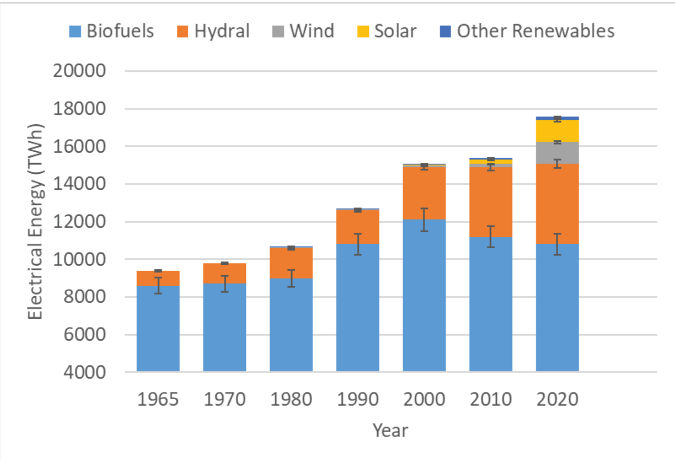

Figure 2: Comparison of global renewable energy consumption [10], [18].

A. *Solar energy harnessing*

In its simplest definition, solar energy is considered to be the energy that is derived from the Sun. It can be harnessed as electrical energy through the utilisation of photovoltaic (PV) cells and concentrated solar power methodologies [33]. The thermal energy of the Sun can also be obtained directly in order to heat water and living spaces, or stored using molten salt technology for later usage [34]. Solar energy, harnessed from the sun's rays, can be utilized directly for various applications, enhancing its ecological and economic benefits [35]. One of the most common methods is through solar thermal systems, where sunlight is captured to heat water for residential use, swimming pools, or industrial processes. Photovoltaic panels convert sunlight into electricity, powering homes, businesses, and electric vehicles directly [36]. Additionally, solar water pumps can irrigate agricultural lands in remote areas, improving food security. By embracing direct solar energy applications, we not only reduce dependency on fossil fuels but also promote sustainability and energy independence, contributing positively to the environment [37].

Photovoltaic cells are perhaps one of the most mainstream methods of harnessing solar energy. The PV cells consist of a layer of semiconductor material that receives and absorbs photons of light and, in turn, generates a corresponding number of electrons. These electrons are siphoned off to drift around a circuit for utilization. The phenomenon is illustrated in Fig. 3. The semiconductor material used is often silicon, although other, more effective materials are being used in modern PV cells, such as graphene and some organic compounds [34], [38].

At present, Saudi Arabia is increasingly investing in solar energy harnessing as part of its Vision 2030 strategy to diversify its energy sources and reduce dependence on fossil fuels. The country boasts an immense solar potential due to its high solar irradiance, with an average of 2,200 kWh/m^2 annually [39]. Currently, Saudi Arabia has installed over 4 gigawatts (GW) of solar capacity, encompassing both photovoltaic (PV) solar cells and concentrated solar power (CSP) plants. Notably, the Sakaka PV Solar Plant, with a capacity of 300 megawatts (MW), is one of the largest PV projects in the region. Additionally, the country is developing large-scale CSP projects, such as the 2 GW Sudair Solar Power Plant, which aims to supply clean electricity and support the national grid. These initiatives aim to harness Saudi Arabia's vast solar resources, with projections suggesting that solar energy could meet up to 50% of the country's electricity demand by 2030, significantly contributing to sustainable development and economic diversification efforts [40].

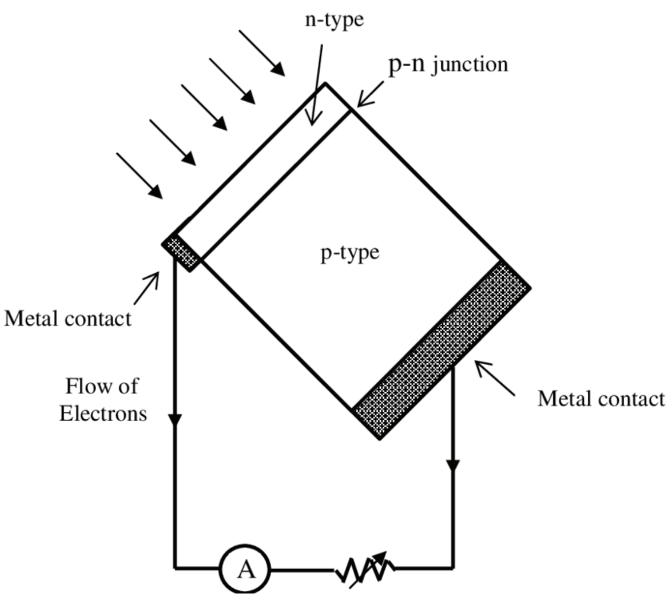

Figure 3: Working mechanism of a PV cell [34].

1. Recent advancements in PVC (perovskite, OPVs, and quantum dot solar cells)

Recent advancements in solar photovoltaic (PV) technologies, particularly perovskite solar cells, organic photovoltaics (OPVs), and quantum dot solar cells, are significantly influencing the field of solar energy [41], [42]. Perovskite solar cells stand out due to their high efficiency and low production costs, achieving power conversion efficiencies exceeding 25%. However, their stability is a concern, with sensitivity to moisture, heat, and light leading to degradation [43]. Ongoing research focuses on enhancing stability and developing scalable manufacturing processes like spin-coating and vapour deposition [44].

Organic PVs leverage organic materials like polymers, offering flexibility, lightweight design, and aesthetic versatility. Recent improvements in material design have raised their efficiency to over 18%, significantly up from below 10% [41]. Their flexibility allows for innovative applications, including roll-to-roll manufacturing for various installations. An improved efficiency of trigeneration plants is achieved through the cogeneration of heat, electricity, and cold. Results show an increase in the system's energetic efficiency to 22.9-27.8% and thermal efficiency to 23.2-26.7% [45].

Quantum dot solar cells utilize semiconductor nanocrystals for superior light absorption and customizable band gaps, enhancing efficiency [46]. Recently, researchers explored the type II-VI semiconductors in PV cell manufacturing due to their wide bandgap properties, which offer high electron mobility, thermal stability, and radiation damage resistance [47]. Despite challenges such as film uniformity and scalability, research continues to optimize the PV cell stability, efficiency, and performance [48].

- **Recent developments in perovskite solar cells**

Literature shows that perovskite-based solar cells have transformed photovoltaics, emerging as frontrunners in next-generation energy harvesting since the first solid-state perovskite cells were developed in 2012. Power conversion efficiency (PCE) has rapidly improved, reaching 25% in 2023, fuelled by advancements in materials, device structures, and processing techniques. The unique optoelectronic properties of hybrid organic-inorganic perovskites, such as high absorption coefficients, tunable band gaps, and efficient charge transport, make them superior to traditional silicon solar cells while simplifying manufacturing [41].

Recently, inverted perovskite solar cells (IPSCs) have also made significant strides, with PCE climbing from 3.9% in 2013 to a certified 26.1% in 2023. This progress is largely due to the development of innovative organic hole-transporting materials (HTMs) that improve charge transport and enhance device stability. Ongoing research into small molecule HTMs and conjugated polymers holds promise for further optimizations, which are crucial for the commercialization of IPSCs and sustainable energy solutions [49].

Additionally, integrating mixed halide wide-bandgap perovskites into tandem photovoltaic systems presents further efficiency enhancements. To address halide phase segregation that affects performance, incorporating pseudo-halogen thiocyanate (SCN) ions has shown success in improving crystallization and reducing grain boundaries. This substitution helps stabilize the structure during operation. Recent achievements in dual-junction configurations have reached efficiencies of up to 25.82% (certified 25.06%) while maintaining over 1,000 hours of operational stability, indicating a promising future for high-efficiency tandem solar cells [50].

- **Recent developments in quantum dot solar cells**

  Recent advancements in quantum dot technologies have significantly enhanced their potential applications, particularly in the realms of display technologies and quantum computing. The development of eco-friendly colloidal quantum dot light-emitting diodes (QLEDs) illustrates a breakthrough in achieving superior luminescence properties while mitigating environmental concerns. Specifically, the integration of interfacial potential-graded ZnSeTe quantum dots has been shown to alleviate interfacial lattice mismatches and minimize strain-related defects, a persistent challenge in the fabrication of efficient green light-emitting devices. These advancements have resulted in devices achieving external quantum efficiencies of 21.7% at 520 nm, establishing a new benchmark for green QLED performance [51].

  The recent recognition of researchers Aleksey I. Ekimov, Louis E. Brus, and Moungi G. Bawendi with the Nobel Prize in Chemistry for their pioneering work in semiconductor nanocrystals underscores the crucial role quantum dots play in diverse applications. Their discoveries have laid the groundwork for a plethora of technological advances. Consequently, the remarkable versatility of quantum dots continues to inspire ongoing research and development across multiple scientific domains [52].

  Therefore, advancements in perovskite, organic, and quantum dot solar technologies could be the key to improving efficiency, reducing costs, and expanding solar energy applications, contributing to more sustainable energy solutions.

B. Concentrated solar power

Concentrated Solar Power (CSP) is a more recent implementation in the area of solar power, although the idea goes back to 200 BC when Archimedes supposedly used mirrors to focus the sun rays on invading Roman triremes and burned them [53].

CSP can be implemented in several forms, such as parabolic troughs, power towers, and solar dishes; however, the key objective remains the same: to focus solar energy on a focal point in order to harness it in the form of thermal or light energy. This focal point is often a solar power tower [54]. Solar energy is considered a cheap, abundant, and inexhaustible source of renewable energy, which can help society reduce its dependency on traditional fuels. Due to its continuous supply, it can offer energy security and independence. Furthermore, it is environmentally friendly, consistent, and a clean source of energy [55].

IV. Viability analysis of renewable energy in Saudi Arabia

The following sections provide the greenhouse gas emissions, energy demand, and consumption trends in Saudi Arabia and the GCC region, highlighting the reliance on fossil fuels for energy production. Rising emissions pose environmental challenges, with recent shifts in energy use and emission statistics. Saudi Arabia's Vision 2030 and regional strategies aim for sustainable growth and climate mitigation, balancing economic development with environmental sustainability. Understanding these dynamics is crucial for assessing progress toward a greener, more sustainable future in the region.

A. GHG emission status

The GHG emissions in Saudi Arabia are related to the energy-intensive industries and the utilization of fossil fuels. Saudi Arabia's electrical energy demand is rapidly increasing due to high population growth and urbanization, primarily generated from petroleum, contributing over one-third of the nation's greenhouse gas emissions [39]. The current energy demand in Saudi Arabia is at an all-time high. According to Wogan and colleagues [56], the average growth in annual energy demand of the kingdom was about 7 percent, and it consumed up to 274.5 terawatt-hours (TWh) of electricity in the same year. The energy consumption of Saudi Arabia is predicted to surge threefold by the year 2030, as stated in the Saudi Vision 2030 [2]. The King Abdullah Petroleum Studies and Research Centre (KAPSARC) estimated that the demand will reach 365.4 TWh by the year 2030 [57].

The Gulf Cooperation Council (GCC) countries, which include Saudi Arabia, the UAE, Kuwait, Qatar, Oman, and Bahrain, collectively contribute a substantial portion of global GHG emissions,

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primarily due to oil production and consumption [58]. Greenhouse gas (GHG) emissions in Gulf countries have been a significant focus due to their heavy reliance on hydrocarbons for economic growth. Saudi Arabia, as the largest economy in the region and a leading oil exporter, is a major emitter. In 2023, Saudi Arabia was responsible for approximately 1.5% of global CO_2 emissions, producing around 805.2 million metric tons of carbon dioxide equivalent (CO_2eq) according to the European Commission, Joint Research Centre [59]. In contrast, while the United Arab Emirates has made notable advancements in renewable energy development, its per capita carbon emissions remain significantly high, estimated at approximately 22.5 tons per individual in 2020. This staggering figure positions the UAE among the highest carbon emitters globally, largely attributed to the predominance of carbon dioxide emissions originating from the combustion of fossil fuels for electricity generation and the operation of vehicles and energy-intensive machinery [13]. This juxtaposition underscores the formidable challenge faced by Gulf nations, including Saudi Arabia, as they navigate the delicate equilibrium between fostering economic growth and adhering to sustainable environmental practices amidst escalating global pressure to mitigate emissions [60].

While per capita greenhouse gas (GHG) emission levels in the Gulf region are relatively lower compared to China, the United States, and India, these nations remain significant contributors to global carbon dioxide emissions [39]. The GHG emissions of Saudi Arabia exhibit a volatile trend. Specifically, emissions per capita were recorded at 18.5 metric tons of CO_2eq in 2010, subsequently rising to 21 metric tons of CO_2eq by 2016, a change primarily driven by rapid industrialization (Fig. 4). However, this figure decreased to 18.7 metric tons of CO_2eq in 2019 as a result of proactive renewable energy initiatives. Current projections from the ECJRC indicate that these emissions are expected to rise to approximately 22.2 metric tons CO_2eq by the end of the current year [59]. Kuwait's GHG emissions surged in 2022 and 2024, likely due to increased domestic industrial activities like oil extraction and energy production, driven by post-pandemic economic recovery, boosting energy use. In contrast, Qatar's emissions remain stable, possibly due to earlier renewable energy investments and efficiency measures. The sharp spikes in Kuwait suggest temporary increases linked to specific industrial expansions rather than long-term trends [61].

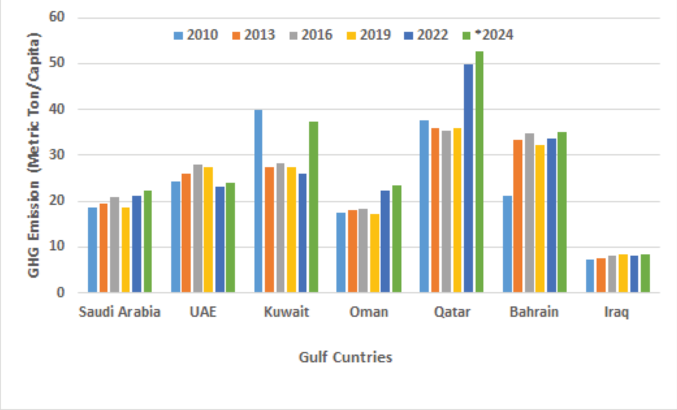

Figure 4: GHG emission data (2010 to 2024) of various Gulf countries [59].

The emission data of CO_2 and CH_4 from the Saudi Arabian energy sector are presented in Fig. 5. As depicted here, in 2010, the annual carbon dioxide (CO_2) emissions for the country were reported at 492.2 million tons, which increased to 532.9 million tons by 2023 [62]. This represents an increase of approximately 8.4% over the thirteen-year period. A comparable trend has been observed regarding methane (CH_4) emissions, which decreased slightly from 49.7 million tons of CO_2eq in 2010 to 47.9 million tons of CO_2 equivalent in 2023. Previous studies have indicated that electricity generation is a significant contributor to CO_2 and CH_4 emissions in Saudi Arabia. In alignment with Saudi Vision 2030, the nation is actively pursuing strategies to reduce greenhouse gas (GHG) emissions, including the gradual removal of fossil fuel subsidies. Moreover, the country has set a goal to mitigate its annual emissions by up to 130 million metric tons of carbon dioxide by the year 2030 [39].

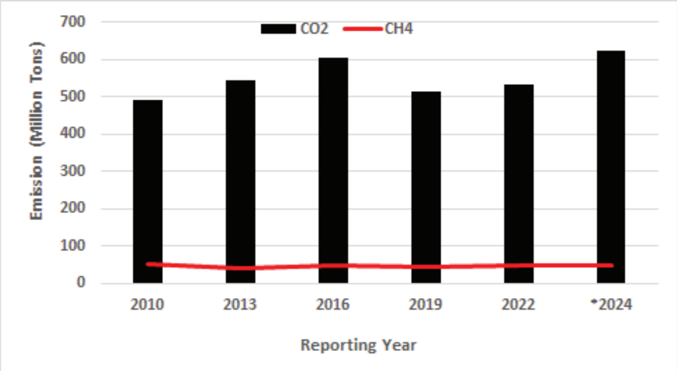

Figure 5: Data of GHG emission (CO_2 and CH_4) from the Saudi Arabian energy sector [62].

As per its updated Nationally Determined Contributions (NDCs), the Kingdom aims to reduce, avoid, and remove GHG emissions by 278 million tons of CO_2eq annually by 2030. This target is a

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sizeable increase versus the previous target of 130 million tons of CO_2eq annually [62]. It is expected that with the tangible efforts to transform from conventional energy sources to renewable options, the GHG emissions will be significantly reduced.

B. Energy demand and consumption

Electricity consumption in the Gulf Cooperation Council (GCC) countries has been on a steady rise due to rapid urbanization, population growth, and economic diversification efforts. As of recent data, the average electricity consumption per capita in GCC countries is among the highest globally. For instance, in 2021, Qatar had one of the highest per capita electricity consumption rates at approximately 14,500 kWh, followed closely by the UAE and Kuwait [63]. The energy consumption in Saudi Arabia is on the higher side, mainly due to the presence of huge industrial setups in Jubail and Yanbu. As shown in Fig. 6, the electricity consumption per capita values are generally in third place among the Gulf countries; however, it is still about 3 times higher than the world average value of electricity consumption [64]. Saudi Arabia's electricity consumption, while significant, is slightly lower, with a per capita consumption of around 8.2 MWh reported for the same year [65]. Despite Saudi Arabia's larger population, the efficiency initiatives and renewable energy projects under Vision 2030 aim to optimize electricity consumption. Consequently, while all Gulf countries grapple with rising demand, Saudi Arabia's unique strategies might influence its future consumption trends compared to those of its neighbours.

The annual increase in the energy demand in Saudi Arabia is about 3000 MW, which is significantly higher compared to other countries. An investment of 1125 billion dollars to meet the energy demand of the country between the years 2009 and 2018 is reported. According to Alaidroos and co-workers, the country utilized about 100 million barrels of oil during 2009 to generate electricity. Saudi Arabia consumes more than 25% of the crude oil within the country annually [66]. About 53% of the power is consumed by households, and the highest consumption is for air conditioning. According to estimates, the electricity demand will increase from 46,000 MW to 120,000 MW from 2019 to 2039. This scenario shows that the oil consumption will accelerate by at least 100% during the next 10 years if renewable energy options are not adopted accordingly [67].

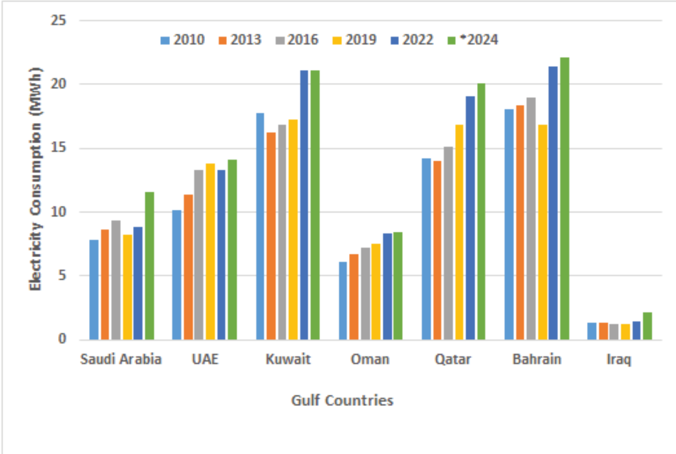

Figure 6: Electricity consumption data of various Gulf countries [39], [59].

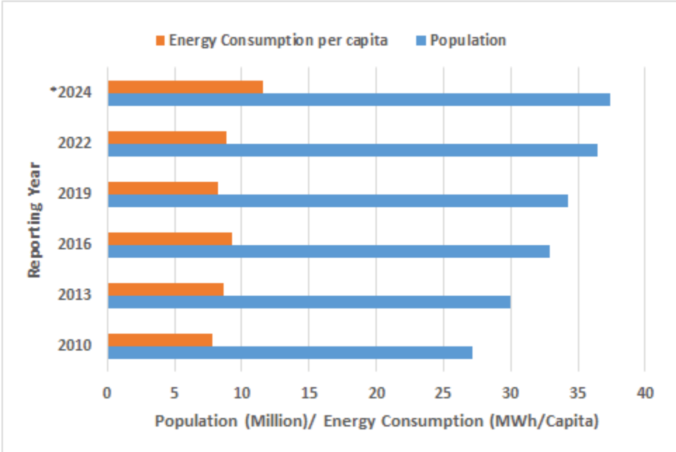

Figure 7: Temporal data of population and electricity consumption for Saudi Arabia [39], [59].

As illustrated in Fig. 7, the population of the country, alongside per capita energy consumption, has shown an upward trend over the past fourteen years [39], [59]. The population has increased from 27.1 million in 2010 to 33.95 million in 2023. Concurrently, although energy consumption saw an uptick, the Gross Domestic Product (GDP) witnessed a growth of approximately 33.72% from 2010 to 2023 [68]. In terms of energy consumption, per capita electrical energy usage rose from 7.8 MWh in 2010 to 10.64 MWh in 2023 [69]. As depicted in Fig. 5, electricity consumption in Saudi Arabia is consistently increasing, while other Gulf countries, including Kuwait, Qatar, and Bahrain, exhibit even higher consumption levels.

Given the correlation between energy production, consumption, and greenhouse gas (GHG) emissions, the country has undertaken various initiatives aimed at GHG mitigation, particularly within the energy sector. As illustrated in Fig. 8, total electricity production is on the rise over time, highlighting the urgent need for decisive action to address the growing emissions. For instance, the country has initiated the replacement of conventional single-cycle power plants with more efficient combined cycle and cogeneration power plants [70]. Furthermore, the Saudi Vision 2030 outlines an ambitious plan to install 58.7 gigawatts (GW) of renewable energy resources, primarily focused on electricity generation [71]. Nevertheless, additional measures could be explored in the electricity sector to further promote GHG reduction, such as the implementation of poly-generation, combined heat and power (CHP) systems, microgrids, waste-to-energy technologies, and biomass plants [39].

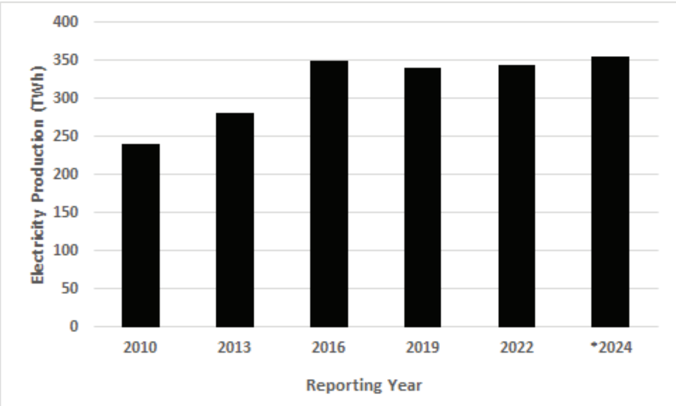

Figure 8: Temporal total electricity production from all producers in Saudi Arabia [39], [59].

V. Solar energy potential in Saudi Arabia

In most of the Gulf countries that are receiving scorching solar flux almost all year round, solar energy can play a key role [72]. Where the average availability of solar flux in European countries is 1 kWh/m^2/day and about 1.7 kWh/m^2/day in Greece, it is 4 to 7.5 kWh/m^2/day in Gulf countries, which is more than five times the stated European values [73]. The Kingdom of Saudi Arabia is one of the most promising countries in the world in terms of developments in the solar energy sector. This is chiefly due to its opportune location on the equator in the “solar belt”; this is the area circling the equator of the planet and is subject to high amounts of solar radiation annually. This puts Saudi Arabia in a favourable position to spearhead the development of solar power technologies.

Additionally, researchers in Saudi Arabia analysed the impact of mineral production and human capital on renewable and solar energy production using a Cobb-Douglas production function. Findings indicate that mineral production positively influences energy generation at low and medium quantiles, while human capital benefits all quantiles. However, geopolitical risk threats increase and acts reduce these energy dynamics across all quantiles. The study recommends optimizing mineral resources to achieve Saudi Arabia’s renewable energy goals [74].

Public awareness about environmental issues and the benefits of renewable energy is also very important in implementing the transition. A study in Dammam, Saudi Arabia, found that while most Saudis have a moderate understanding of renewable energy, 79.2% are concerned about pollution and recognize the benefits of alternative energy. However, 97.2% believe the high costs of renewable technologies hinder their effectiveness. To meet the goals of Saudi Vision 2030, it’s crucial to implement strategies that enhance awareness of renewable energy across all demographics and encourage the integration of these technologies into daily life for improved environmental sustainability [75].

A. Comparison of renewable energy sources in Saudi Arabia

Saudi Arabia, traditionally known for its vast oil reserves, is increasingly exploring renewable energy potentials to diversify its energy mix and reduce carbon emissions. Saudi Arabia presents a promising landscape for renewable energy development, particularly in solar, wind, and geothermal energy. Solar energy leverages the country’s abundant sunlight, with over 3,000 hours of sunlight annually, making it a prime candidate for large-scale power generation. Significant investments in solar technology, exemplified by projects like the Mohammed bin Rashid Al Maktoum Solar Park, demonstrate the viability of this resource [76]. However, challenges such as solar energy’s intermittency and the need for infrastructure upgrades pose hurdles. Wind energy complements solar production by providing power during less sunny periods, though site limitations and environmental concerns necessitate careful planning for sustainable deployment. Geothermal energy, while stable and efficient due to its independence from weather conditions, faces challenges of high initial costs and exploration limitations, as the country lacks extensive geothermal infrastructure. A balanced energy strategy should incorporate all three sources. Solar energy is set to dominate the renewables landscape, aligning with Saudi Arabia's Vision 2030 goals [2]. Geothermal energy, although not a primary focus at present, warrants further exploration for its potential contribution to a diversified energy portfolio.

Ultimately, a holistic approach that includes multiple renewable resources will be essential for Saudi Arabia in achieving a sustainable energy future. Table 2 presents a comprehensive examination of Saudi Arabia's energy potential by delineating the advantages and challenges associated with various energy sources. This table succinctly summarizes the comparative benefits and drawbacks of solar, wind, and geothermal energy, emphasizing their prospective roles within the kingdom's energy landscape.

Table 2: Comparative analysis of energy potential in Saudi Arabia: Advantages and challenges across diverse energy sources

Energy Source	Advantages	Challenges
Solar	**Abundant Resource:** High solar irradiance, with over 3,000 hours of sunlight annually in Saudi Arabia.	**Intermittency:** Subject to daily and seasonal variations, necessitating energy storage solutions or backups.
	Technological Advancements: Significant investments and successful projects like the Mohammed bin Rashid Al Maktoum Solar Park.	**Infrastructure Needs:** The Current electricity grid may require upgrades, and initial PV system installation can be costly.
	Environmental Benefits: Clean energy source that produces no emissions during operation, aiding in carbon footprint reduction.	
Wind	**Complementary to Solar:** Generates electricity during periods of low solar output, enhancing energy supply stability.	**Site Limitations:** Optimal locations for wind farms are limited to specific regions, requiring extensive feasibility studies.
	Growing Technology: Rapid advancements in wind technology have led to improved efficiencies and reduced costs.	**Environmental and Social Concerns:** Potential impacts on local wildlife and community opposition regarding land use.
Geothermal	**Stable Energy Supply:** Provides a consistent and reliable power source independent of weather conditions.	**Limited Sites:** Exploration in Saudi Arabia is in early stages, lacking the infrastructure found in more developed geothermal regions.
	Low Land Footprint: Requires less land area compared to solar and wind energy installations.	**High Initial Costs:** Involves substantial upfront costs for drilling and exploration.

Saudi Arabia is at a pivotal moment in its energy transition, possessing significant potential to leverage renewable resources. While solar energy is poised to dominate due to its ample availability and decreasing costs, wind and geothermal energy can enhance a diversified energy portfolio. An integrated renewable strategy may mitigate environmental impacts while fostering economic growth and ensuring energy security.

B. *Status and current efforts*

As per the targets of Vision 2030, efforts have been made and in addition to practical application, i.e, installation of renewable energy components, research in the field of solar power and PV cells has been ongoing in Saudi Arabia since the early 1960s [77]. The development of solar energy technologies began in Saudi Arabia in 1977, and it was conducted by King Abdulaziz City for Science and Technology (KACST). Their first project was the "Solar Village" project, which started in 1980 and aimed to provide power to three villages in the countryside utilising only solar energy [78].

A study conducted by Pazheri mentioned the execution of the first rooftop 2 MW PV system mounted on the roof of King Abdullah University of Science and Technology (KAUST) in Saudi Arabia during the year 2010 [79]. During the same year, a desalination plant started operating, utilizing 10 MW of energy produced from solar power plants in Al-Oyainah and Al-Khafji. Saudi Arabia's first solar power plant was commissioned on Farasan Island, which is located in the southeast of the Red Sea, in October 2011. It is a 500 kW solar PV plant with a generation capacity of 864 MWh/year [80].

In 2012, Princess Noura University for Women (PNUW) launched an innovative thermal solar plant, recognized as the largest of its kind globally. This facility spans an extensive area of 36,160 square meters and boasts a power generation capacity of up to 25 megawatts [78]. Additionally, a noteworthy development is the photovoltaic carport system established by Saudi Aramco at its headquarters in Dhahran. Able to produce up to 10 megawatts of power, it is the largest solar carport in the world and provides parking spaces for up to 4,500 cars at any one time [62].

During the year 2012, a solar park built by Aramco King Abdullah Petroleum Studies and Research Centre in Riyadh was extended to 5.3 MW from 3.5 MW. Similarly, a solar thermal plant was built on an area of 36,300 m^2 [58]. Vision Electro Mechanical Company, which is a subsidiary of Construction Products Holding Company, established a budget of $150 million in order to develop, construct, and operate solar power plants in the country. A solar village project covering an area of about 68,000 m^2, built near Al-Jubailah, Al-Higera, and Al-Uyaynah, 50 km from Riyadh, provides 1 to 1.5 MWh/d of electric energy. The plant consists of 350 computerized solar PV concentrator electricity-generating power units that comprise 160 PV arrays over an area of 4000 m^2 [70].

To date, several studies driven by the Saudi Vision 2030 objectives have been done to evaluate the renewable energy option in the kingdom, and it is reported that solar energy could be one of the renewable energy sources with copious technological progression in electricity production since the last half century [81]. At present, Saudi Arabia is among the six Gulf Cooperation Council countries emerging as a leading market for photovoltaic (PV) ventures. It is anticipated that the country will lead the region and act as a hub for solar energy deployment [40].

A recent review study on the integration of renewable energy into Saudi Arabia's current energy framework and its effects on reducing greenhouse gas (GHG) emissions. Their study analyzed GHG emissions from key sectors, including industrial processes, energy, agriculture, and waste. They focused on primary renewable energy sources, including solar photovoltaic (PV), to assess GHG emissions from the energy sector. The researchers noted that, as of 2020, Saudi Arabia's total renewable energy capacity had exceeded 400 MW. However, the country has launched various initiatives in partnership with different entities aimed at achieving a renewable energy generation capacity of 58.7 GW by 2030, which is expected to lead to a significant reduction in GHG emissions. Challenges such as high temperatures and sandstorms pose significant obstacles to the implementation of large-scale solar PV systems in Saudi Arabia [82]. The relationship between renewable energy and GHG emissions has been extensively explored, and several real-time and ongoing projects have already been initiated to mitigate GHG emissions [80].

Khan et al. examine the use of smart grid technologies to enhance renewable energy deployment in Saudi Arabia, focusing on improving energy efficiency, demand balance, and operational costs. Solar energy is the main renewable source, and a feasibility analysis is recommended to determine the optimal energy mix while ensuring grid security and reliability. The country's significant solar potential necessitates supportive regulations, such as net metering and feed-in tariffs, to promote solar PV systems, particularly in construction. However, the current net-metering incentives may not appeal to small consumers [83]. Additionally, security and privacy in smart grids require regulatory oversight, as utilities may compromise these aspects for cost-cutting. A localized standard framework is vital for ensuring interoperability and flexibility in smart grid infrastructure, facilitating efficient data management, and ultimately leading to reliable, sustainable energy systems [84].

In their recent study, Islam and Ali highlighted that Saudi Arabia, even though it is the largest oil producer, needs to align with global targets of CO_2 reduction. Presently, there is no comprehensive energy policy framework to facilitate this sustainable transition. The existing literature lacks efforts to develop such a framework. The study emphasizes the need for strategies in regional collaboration, human capital development, international models, public engagement, resource conservation, and technological innovation to advance the green energy transition from an energy policy perspective [62].

Thus, the key to the success of solar energy utilization in the kingdom is high amounts of global horizontal irradiation (GHI): around 2,400 kWh/m^2 annually, coupled with the vast areas of uninhabited desert ripe for development of huge solar power facilities. These opportunities, give great potential for Saudi Arabia to adopt solar power as the chief source of their energy [84].

C. Current limitations and obstacles in exploiting solar energy

Amongst other installation and operational issues, the major issues with solar powered systems are relatively high capital cost, storage limitations, interrupted supply, and high operation and maintenance costs. At the local level, there are two most significant factors, dust and high temperatures, which limit the application of solar panels by reducing the efficiency of the solar panels [85].

Soiling is one of the major issues currently faced in the implementation of solar technologies in Saudi Arabia. Dust, which is present in large amounts in the atmosphere due to the desert climate, often accumulates on the solar cells. This causes a reduction in the efficiency of the solar panels, requiring regular cleaning, often on a daily basis, in order to maintain maximum efficiency of the cells. This inadvertently leads to an increase in maintenance expenditures [86].

Researchers argue that, ironically, high temperatures also negatively affect the efficacy of PV cells. 'The increased temperature in the cell increases atoms [sic] vibration, which obstructs charge carriers [sic] movement and decreases cell efficiency' [87]. Other factors decreasing the favourability of solar energy are huge energy subsidies by the Saudi government, as well as the unpredictable nature of the availability of sunlight.

D. Strategies to overcome obstacles in harnessing solar energy

During the last five years, significant technological advancements enhanced the efficiency of solar cells, which brought down the cost of solar energy considerably. It is expected that the upcoming advancements in technology, energy storage, and enhancements in solar cell production will further reduce the cost of solar energy [88]. In order to overcome dust and high temperature issues, several studies brought promising solutions to handle these challenges, which include coatings, electrodynamic screens, and air blowers. These improvements will certainly capitalize on their adeptness and provide significant financial improvements. To date, these enhancements in solar energy technologies have brought about more than a 50% reduction in their costs, which is anticipated to continue and, in the long run, will accelerate their global adoption [55].

Auspiciously, as energy costs are increasing globally, the cost of solar energy is decreasing. It is reported that the normalized energy cost of solar PV at the global level is anticipated to reduce by 60% within the next decade [89]. In fact, it is stated that about a 90% decline in the solar PV was achieved by the year 2019 which shows the promising scenario for rapid adaptation of solar energy [90].

Energy storage is a prime factor in solar energy exploitation, as standalone photovoltaic systems cannot produce electricity around the clock [75]. The cost of photovoltaic systems is generally higher as they demand larger storage arrangements. Solar technologies, and PV cells in particular, have advanced further in the last decade than ever before. It is now economical and feasible to employ them over other options, largely due to the major reductions in PV cell manufacturing, installation, and maintenance costs. However, now, the grid integration of solar energy systems offers solutions to such limitations in addition to improving the quality of power output and reliability [91], [92].

However, none of these issues hampers the viability of solar power when compared to the current fossil-fuel-based energy economy of the kingdom [77]. Due to the development of anti-soiling coatings for PV cells, dust accumulation on the panels is no longer an issue. Conversely, the coatings are also anti-reflective and hence maximize the amount of solar energy harnessed by the cells. Concerning the overheating of PV cells, the implementation of cooling mechanisms, such as the one illustrated in Fig. 9, greatly reduces panel temperatures. On the contrary, it actually improves the performance of the cells and increases their efficiency [93]. Furthermore, integrated bifacial solar panels with cooling mechanisms may further improve the efficiency of solar cells [94].

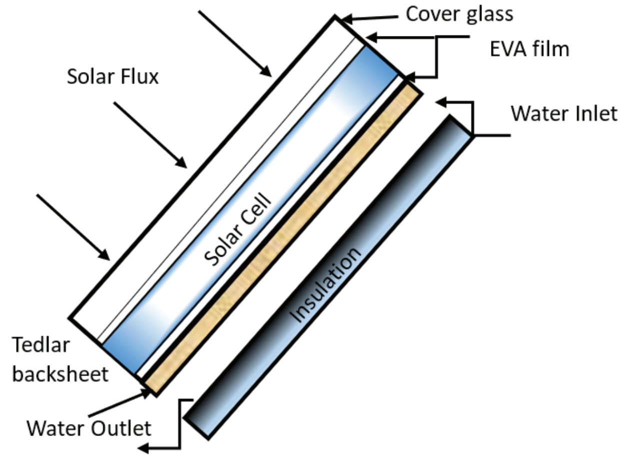

Figure 9: Suggested water cooling mechanism for PV cells.

E. Techno-economic analysis

While performing a techno-economic analysis, it is necessary to consider the environmental, health, and economic factors in addition to the access to solar energy, the geographic position of the power station, and the load estimates of the country. A barrel of oil could deliver 1,700 kWh of electrical power, and the production cost of each kWh in Saudi Arabia is $0.1 (maximum), and the average cost is about $0.03, which is considered a low price [95]. However, Saudi Arabia is burdened with about $188 billion to cover the expenses between prices and costs in the form of subsidies [96]. Regarding job creation in the renewable sector, an increase of up to 300% is expected by the year 2030, with a likelihood of about 80,000 jobs in Saudi Arabia. If the cost of health and environmental compensations is considered, the cost of solar energy production will be lower than the cost of energy produced from conventional fuel in Saudi Arabia [81].

The trends in carbon monoxide (CO) emissions are certainly linked with the energy generation and consumption levels, which in turn affect the cost of energy and its accessibility. In order to evaluate the techno-economic viability of solar energy in Saudi Arabia, the subsidies that result in overuse and incongruous distribution of oil and natural gas resources need to be considered. Furthermore, the dependency of Saudi Arabia's GDP on energy export revenue plays an important role in the Saudi economy [91]. As Saudi Arabia is among the few fast-developing countries on the planet, the reduction of GHG emissions is indispensable, which necessitates the switching from conventional to renewable energy sources [95].

It is vital to include the indirect costs of conventional energy if a techno-economic comparison needs to be done between conventional and renewable solar energy [97]. The average indirect costs of CO_2, SO_2, and NO_x for Saudi Arabia are calculated as $ 0.4/kg, $ 34.4 /kg, and $ 164.8/kg, respectively. While the net indirect costs estimated are 0.1688 SR/kWh [98].

Recently, a study conducted in a rural African region with high solar exposure found that replacing traditional technologies with solar kiosks resulted in an average revenue increase of four times, indicating significantly stronger financial performance. Additionally, they estimate that a 1°C rise in temperature is associated with an increase of $9 in average monthly revenue. The result of this study shows a promising outcome of switching from conventional to renewable energy options [99].

Usman and colleagues performed a techno-economic analysis considering the various hybrid energy system models comprising grid, diesel generators, and solar PV. The analysis was performed based on a blend of renewable energy along with grid-connected hybrid systems. The analysis was performed per unit cost of electrical energy production, which included the operating cost of crude oil-based energy production and a decline in GHG emissions. It was found that the grid-connected system, along with the solar PV option, was the most economical, having a cost of $ 0.115/kWh. However, the renewable fraction of PV is only 18% [100].

Furthermore, the kingdom can adopt an energy management strategy through energy price control and the replacement of fuel. Consumers will reduce their consumption of energy when the cost of energy increases, which will ultimately result in energy-efficient technology adaptation and indirectly achieve a reduction in CO emissions. It is expected that from the year 2020 onward, Saudi Arabia will be able to establish PV Grid Connected (PVGC) power plants along with the traditional power plants to meet the country's required demand [88].

Hajiminehand and Moghani highlight that Saudi Arabia, targeting a 7.5 percent annual economic growth, requires significant energy due to increasing population and industrial demands. The country recognizes that relying solely on crude oil and cheap labor is insufficient for wealth generation, prompting investments in renewable energy to diversify its economy [101]. Positioned advantageously for solar energy, Saudi Arabia is actively attracting private sector investment through public-private partnerships. This transition aims to reduce domestic oil consumption and pollution. Additionally, the government is reforming energy prices to mitigate waste and foster collaboration in science and technology. However, challenges such as technological issues and high initial costs persist, which can be addressed through long-term power purchase contracts to secure stable revenues for investors and protect against electricity price volatility [102].

In addition, Saudi Arabia is implementing various policies, including feed-in tariffs, net metering, and subsidies, to support the energy sector. The country

http://dx.doi.org/10.21622/RESD.2025.11.2.1319

has recently announced a net-metering program with feed-in tariffs set at $0.019/W for residential and $0.013/W for commercial sectors. To facilitate this, KSA is focusing on technical preparations such as installing smart meters and developing building retrofitting solutions. However, the complex pricing framework may make the net-metering policy less attractive for small-scale consumers, like residential homes and small businesses, compared to those having higher energy demands [91].

Kahia and co-workers conducted a study recently, analysing the impact of green energy and environmental innovation on key environmental indicators in Saudi Arabia from 1990 to 2018, using econometric methods like unit root tests and Dynamic OLS. They highlighted that economic growth consistently leads to environmental degradation. While green energy and environmental innovation positively influence environmental quality, their effects are minimal [16]. Therefore, the interaction between green energy, environmental innovation, and economic growth shows a positive net effect, indicating that Saudi Arabia's green sector requires further investment and development. These results highlight the need for effective policies to promote green initiatives and technological innovation.

F. Solar energy employment in Saudi Arabia

Saudi Arabia's strategic geographic positioning confers significant potential for the development of solar energy, owing to its abundant solar irradiance, which averages approximately 2,500 kWh/m² annually. Recognizing this substantial renewable resource, the Kingdom has prioritized the employment of solar power as a central component of its broader energy transition strategy, in alignment with the objectives outlined in Vision 2030 [2]. This vision endeavours to diversify the national energy portfolio, diminish dependence on hydrocarbon resources, and foster a sustainable economic framework [5]. As evidenced by the timeline depicted in Table 3, efforts to promote renewable energy employment in Saudi Arabia commenced over a decade ago, with the announcement of Vision 2030 serving as a pivotal milestone in this trajectory. Within the comprehensive energy mix plan, solar energy emerges as the primary alternative energy source, underscoring its critical role in the Kingdom's sustainable development agenda [84], [101].

Table 3: Renewable Energy Transition and Solar Energy Employment within Saudi Arabia's Renewable Energy Portfolio [8], [77], [84]

Actions/ Objectives	Timeline (Year)	Remarks
Proposal by the King Abdullah City for Atomic and Renewable Energy (KA-CARE)	2012	Kingdom adopted a proposal submitted by KA-CARE to add 23.9 GWe of renewable capacity by 2020 and 54 GWe by 2032
Initiation of Vision 2030	2016	Vision 2030 was announced, and action started.
Establishment of the Saudi National Atomic Energy Project (SNAEP)	2017	The cabinet approved the establishment of the Saudi National Atomic Energy Project (SNAEP)
Establishing Renewable Energy Program	2020	The government approved the funds.
Plan for First Nuclear Reactor	2023	Kingdom makes an agreement to build a nuclear power plant and switch to a comprehensive safeguards agreement with the International Atomic Energy Agency (IAEA)
Achievement of Specific Energy Efficiency Goals	2025	Funds are released, and organizations are working on their targets.
Targeted time for achievement of Vision 2030	2030	Work is in progress with a slight time delay
Achievement of Sustainable Economy Goals	2040	Work is in progress with a slight time delay

Among several studies targeting the employment of solar energy in the Kingdom, a comprehensive study utilizing data from King Abdullah City for Atomic and Renewable Energy (2017–2021) analysed solar resource patterns across various regions of Saudi Arabia. Researchers classified the country's solar stations into five geographical groups based on regional climate variations and solar radiation profiles. Meteorological variables such as air conditions, wind patterns, humidity, and barometric pressure were examined across 44 stations, providing valuable insights for optimizing solar resource allocation and integration into the national power grid. These findings support strategic planning for large-scale solar projects, ensuring efficient utilization of the country's solar potential [103].

Saudi Arabia's renewable energy development timeline reflects a clear commitment to this transition. In 2012, KA-CARE proposed adding 23.9 GWe of renewable capacity by 2020 and 54 GWe by 2032, a plan adopted by the Kingdom. The initiation of Vision 2030 in 2016 marked the formal start of large-scale reforms, including the establishment of the Saudi National Atomic Energy Project (SNAEP) in 2017 to diversify energy sources further. The government approved funding for renewable energy programs in 2020, accelerating project deployment.

By 2023, Saudi Arabia had achieved a total installed renewable capacity of 2.8 GW, with over 8 GW under construction, demonstrating significant progress. The country also plans to build its first nuclear reactor, with agreements in place to enhance its energy diversification efforts. Key milestones include reaching energy efficiency goals by 2025, with the overarching target of achieving a sustainable, low-carbon economy by 2040 [86].

From solar energy employment in the Saudi Arabia point of view countries' concerted efforts, supported by detailed resource assessments and strategic planning, position it as a regional leader in solar energy. These initiatives not only aim to reduce carbon emissions projected to decrease by up to 35% by 2030 but also foster economic diversification and environmental sustainability [2].

G. Actions and Accomplishments Based on Vision 2030

Saudi Arabia has presently introduced initiatives for renewable energy, including solar energy adaptation, by involving the private sector. Major governmental entities, including the Ministry of Energy, Industry, and Mineral Resources (MEIM), Electricity and Cogeneration Regulatory Authority (ECRA), Ministry of Commerce and Industry (MCI), Renewable Energy Project Development Office (REPDO), and General Investment Authority, have a leading role in implementing these targets. In addition to that, a significant increase in downstream assets in the renewable energy sector, an increase in power tariffs, and an enhancement in efficiency are paving the path for renewable energy in the Kingdom [104]. According to the Vision 2030 of Saudi Arabia, the Kingdom will generate 9.5 GW from renewable energy sources (including solar) by the year 2023 and 54 GW by the year 2040 [2].

Subsequently, the nation revised its objectives to attain a renewable power capacity of 27.3 GW by 2023 and 58.7 GW by 2030. Nevertheless, based on the current pace of renewable energy development, averaging 0.1 GW per year from 2010 to 2021, it is estimated that there is a shortfall of 25.8 GW in meeting the 2023 target [105].

Saudi Vision 2030 considers renewable energy as one of the pillars for the country's economic standing. The Kingdom is determined to attain self-reliance by focusing on the various significant branches of the Saudi economy. It is investing in research, design, and development, along with manufacturing-related goods and distribution. Plans according to Vision 2030 give primacy to localizing the manufacturing and fabrication of related equipment in the local industries. The legal and governing structure is being reviewed to improve the procuring and investing opportunities in the private sector [2]. After the advent of Vision 2030, a subsidiary program called the National Transformation Program 2020 was launched, which targeted the production of 3.45 GW of renewable energy by the year 2020. This program will help to provide about 4% of the total energy consumption in the country [104].

During the year 2018, the title of the first solar power project was awarded to ACWA Power, having a capacity of 300 MW in Al Jouf. This project is part of the National Renewable Energy Program, which has a target of generating 9.5 GW from renewable energy sources by the year 2023. This share of energy will be sufficient to power more than 40,000 houses in the country [106]. At the time, it is necessary to validate the balance between socioeconomic and environmental factors because the cost of renewable energy technologies is higher, at least at present, which is the prime hindrance to adaptation to the new renewable energy era.

VI. Discussion on the Current Status and Future Plans

As stated in the Saudi Vision 2030, Saudi Arabia aims to dedicate itself to the transition towards a renewable energy paradigm [2]. As stated earlier, the kingdom initially set a target of producing up to 60 gigawatts by the year 2030, 40 gigawatts of which would be solar power, with the other 20 gigawatts consisting chiefly of wind power and other renewable sources [107]. The kingdom has assigned about $117 billion to this aspiring endeavor [108].

Saudi Arabia has identified several potential sites for the installation of solar photovoltaic (PV) and concentrated solar power (CSP) projects, as detailed in Table 4. This selection process is predicated upon the specific weather and geographical conditions of the respective locations. Notably, the country boasts a substantial direct normal irradiation (DNI) resource, averaging approximately 2200 kWh/m^2 per year, positioning solar energy as a primary source of renewable energy [39].

To address the challenges associated with the large-scale integration of solar PV and CSP systems, Saudi Arabia is actively exploring viable solutions. The Sakaka solar PV project, which has a capacity of 300 MW, is the largest of its kind in the nation, situated in Al Jawf. This project covers an area of 6 square kilometres, and it has achieved a remarkable cost of SAR 0.08775 per kWh, thus setting a new benchmark for low-cost solar photovoltaic energy generation. It is expected that the project will produce around 680 GWh of electricity annually, which is enough to power around 75,000 homes [109]. Additionally, the project is projected to mitigate carbon emissions by approximately 606 kilotons annually. Saudi Arabia has robust potential for solar energy at more than 30 locations, making solar energy the prime renewable energy source for the Kingdom [40].

In its strategic effort to harness solar energy, the Kingdom has established a comprehensive network of 46 weather monitoring stations dispersed across the country. These stations furnish vital meteorological data, including average daily values for direct normal irradiance (DNI), global horizontal irradiance (GHI), and diffuse horizontal irradiance (DHI), recorded at approximately 6,200 Wh/m^2, 5,000 Wh/m^2, and 2,000 Wh/m^2, respectively. These indicators, GHI, DNI, and DHI, collectively highlight the substantial potential for both photovoltaic and concentrated solar energy systems within the Kingdom [39].

Table 4: Solar energy sources and possible location of project in Saudi Arabia [39], [40]

Solar Energy Source Type	Possible Location in Saudi Arabia
Solar Photovoltaic (SPV)	Tuwaiq, Wadi Al-Dawasir, Shaqra, Khushaybi, Waad Al-Shammal, Al-Ras, Yanbu, Sourah, Al-Ghat, Duwadimi, Starah, Dumat Al-Jandal
Concentrated Solar Power (CSP)	Al-Kahafa, Khushaybi, Tabuk, Tabarjal

Several organizations are going to be involved in the accomplishment of Vision 2030 tasks, including the Renewable Energy Project Development Office (REPDO) and Electricity and Cogeneration Regulatory Authority (ECRA). A mega program, the National Renewable Energy Program (NREP), is delivered by REPDO. The aim of REPDO is to improve the share of renewable energy in the Kingdom by providing strategic initiatives to potential candidates. ECRA is responsible for controlling and authorizing the electricity diligence in the Kingdom. It not only manages the power supply and technical matters but also handles consumer issues and other administrative and organizational matters [110].

In order to increase the pace of development in future tasks, REPDO developed a user-generated portal, "We Supply Renewables". The portal allows corporations, companies, and related organizations in the Kingdom to display their services and products to global developers contributing to the NREP. Saudi Aramco and Saudi Arabian Basic Industries Corporation (SABIC) are aiming to increase and improve the development of lightweight, resilient, and integrated PV roof panels for energy production. They are also involved in developing economical and better solar panels, which require less fabrication and installation time [111].

One of the important factors in increasing the pace of renewable energy transformation is the development and implementation of relevant policies and regulations. Researchers have examined the advancement of solar photovoltaic (PV) energy implementation in Saudi Arabia, emphasizing the policies and regulations that have supported its development. A recent study done by Ali (2023) explored the energy landscape in Saudi Arabia and investigated the advancement of solar PV deployment in Saudi Arabia, examining capacity

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additions, growth trends, and the role of regulations and policies in supporting the sector. The researcher highlighted the importance of a comprehensive renewable energy policy for transforming the country's energy landscape towards a sustainable future. They mentioned several regulations and policies in the Kingdom of Saudi Arabia, established by the National Grid (NG), the Saudi Electric Company (SEC), the Water and Electricity and Cogeneration Regulatory Authority (WERA). These regulations, codes, and standards will be very helpful in promoting and successfully deploying renewable energy projects in the Kingdom. Specifically, these policies have proven effective in fostering the expansion of the solar industry in Saudi Arabia, leading to substantial investment and job creation in recent years [109]. Similarly, Al-Sarihi et al. (2023), in a book chapter, assess the reasons behind the underutilization of renewable energy resources in the GCC states, including Saudi Arabia. The authors concluded by highlighting the need for more adaptable policy options that can facilitate the faster adoption of renewable energy within the country [112].

Energy efficiency policies and programs, including energy subsidies and feed-in tariffs (FIT), help implement renewable energy transformation in a country [113]. Saudi Arabia has attractive policies related to commissioning and retro-commissioning with financial incentives and programs. The feed-in tariff for power exported back into the grid in Saudi Arabia currently stands at 1.86 cents and 1.33 cents per kilowatt hour (c/kWh) for residential and commercial applications, respectively. Both home and business owners can now benefit from lower electricity prices that are achievable with solar energy [92]. However, at present, no feed-in tariff policy has been implemented in the Kingdom. Researchers suggest that a feed-in tariff policy tool that promotes investment in renewable energy sources needs to be designed. [114].

Saudi Arabia is streamlining the improved dust repellent coating materials, which are highly efficient in severe weather conditions, such as during dust storms. Furthermore, the Kingdom initiated numerous worldwide entrepreneurship competitions, locally and abroad, which will help in advancing the state-of-the-art solutions for promoting renewable energies and their efficiency [93, 120]. These efforts will result in localizing a substantial share of the renewable energy value chain in the Kingdom's economy. Most of these future ventures are in the direction of self-sustained production of solar energy.

VII. Conclusions

This study contributes to bridging the existing gap in the literature regarding the implementation of solar energy as a primary source of renewable energy in the Kingdom of Saudi Arabia. The country possesses significant potential for solar energy generation across more than 30 sites, due to the high solar flux availability, positioning solar energy as the foremost renewable energy source for the Kingdom. By exploring both global and national contexts, the research highlights the pivotal role that solar energy can play in the Kingdom's energy transformation, particularly in alignment with the ambitious goals set forth in Saudi Vision 2030.

The analysis reveals key limitations and obstacles currently hindering the acceleration of this transition. Notably, the generous subsidies for fossil fuels, along with current pricing structures, pose significant barriers to the widespread adoption of renewable energy technologies. Nevertheless, the continuous advancements in solar energy harvesting efficiency, declining capital costs, and innovative solar cell designs enhance the feasibility of solar energy as a viable alternative.

From an economic perspective, transitioning to solar energy presents considerable long-term benefits for the Kingdom. It not only has the potential to reduce local dependence on conventional fuel sources but also promises increased export revenues and improved financial returns. Moreover, the Vision 2030 initiative aims to localize manufacturing and operational capabilities while fostering private sector investment, which are crucial steps that will expedite the transformation of the Kingdom's energy landscape.

The environmental implications of adopting solar energy are also noteworthy, as the technology can significantly mitigate the negative impacts associated with fossil fuel consumption. This transformation could lead to reduced emissions, lower remediation costs, and ultimately contribute to a cleaner environment. Additionally, the financial incentives, such as savings on electricity bills and potential feed-in-tariff earnings, are likely to garner public support for renewable energy initiatives.

The study advocates for the revision of existing policies and the implementation of clear feed-in-tariff mechanisms, which would facilitate the achievement of the Kingdom's renewable energy targets. The organizational restructuring outlined in Vision 2030 is pivotal for steering the economy towards a more sustainable trajectory. With the partial implementation of this vision, it is anticipated that the Kingdom's economic landscape will evolve significantly by 2030.

In summary, the findings underscore the substantial potential of solar energy to supplant conventional fossil fuels as the country endeavours to meet its increasing energy demands. While the current research provides substantial insights into the potential of solar energy in Saudi Arabia, future studies should explore the techno-economic impacts, cost-benefit analyses, and the relationship between renewable energy consumption, economic growth, and environmental sustainability. Such inquiries will further elucidate the pathways for an effective energy transition and contribute to the Kingdom's overarching goals for sustainable development and reduced carbon emissions.

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CRediT authorship contribution statement

MS. provided supervision throughout the study, contributing to validation, writing review, and editing. All authors have read and agreed to the published version of the manuscript. MTBS. Contributed to the conceptualization, methodology, formal analysis, investigation, and resource management. MABS. Contributed to the writing of the original draft, data curation, and visualization of this research. MA. Contributed to the investigation, resource management, review, and editing. ENM. Contributed to analysis and investigation.

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Data availability

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

Declarations

Ethics approval and consent to participate

Not applicable.

Conflict of interest

The authors declare that they have no competing interests.

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