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Transforming Saudi Arabia's Energy Landscape towards a Sustainable Future: Progress of Solar Photovoltaic Energy Deployment

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Abstract: The Kingdom of Saudi Arabia's electricity sector has undergone several distinct phases, and the country's commitment to renewable energy development has resulted in a modern phase that includes the deployment of renewable energy power plants since 2010. Due to Saudi Arabia's diverse topographical position, the exploration of renewable energy technologies is of interest, particularly solar energy, and its progress in renewable energy development could serve as a model for other countries seeking to transition to clean energy. This article explores the progress of solar photovoltaic (PV) energy deployment in Saudi Arabia, with a focus on the policies and regulations that have facilitated its growth. The article provides an overview of the energy landscape in Saudi Arabia and investigates the progress of solar PV deployment in Saudi Arabia, analyzing growth trends, capacity additions, and the role of policies and regulations in supporting the sector. The focus on renewable energy development in Saudi Arabia, particularly solar PV technology, could have far-reaching implications globally as the world seeks to transition to cleaner sources of energy. This research article highlights the importance of a comprehensive renewable energy policy for transforming the country's energy landscape towards a sustainable future.

Keywords: renewable energy; solar photovoltaic; energy policy and regulations; KSA Vision 2030

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1. Introduction

The conventional framework of the power grid is being altered due to the rising need for renewable energy technologies (RETs) and the prevalence of distributed energy generators [1,2]. As climate change and the depletion of fossil fuels pose serious challenges, renewable energy sources are becoming more significant than ever. Of all the available renewable energy technologies, solar photovoltaic (PV) is considered one of the most promising due to its significant growth and increasing importance as a source of renewable energy on a global scale. It is estimated that the global installed capacity of solar photovoltaics (PVs) will continue to grow in the coming years, reaching an estimated 1630 GW by 2030 and potentially up to 4500 GW by 2050 [3,4], as depicted in Figure 1.

Renewable energy development has become a priority for many countries around the world as they seek to transition to a more sustainable and climate-friendly energy system. Saudi Arabia's Vision 2030 plan aligns with this global trend by aiming to diversify its economy and reduce its reliance on oil through the development of renewable energy sources, particularly solar photovoltaic (PV) technology.

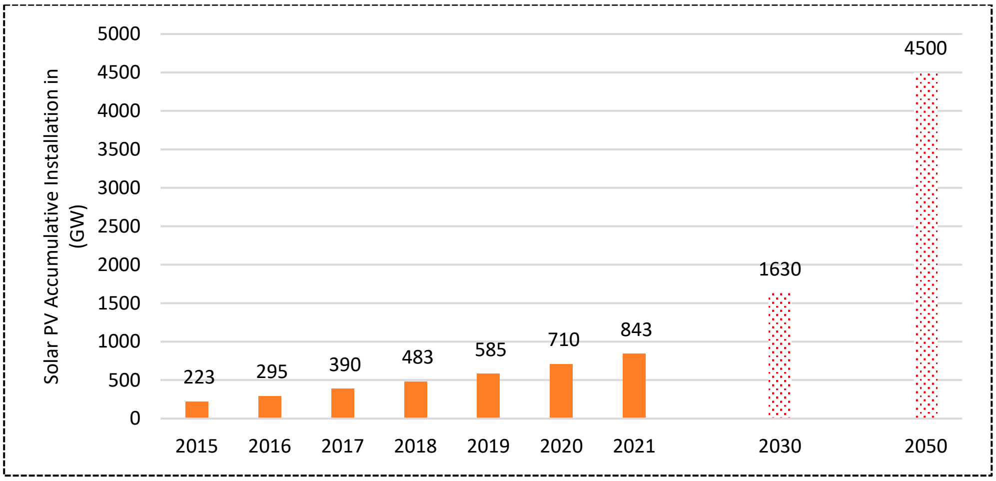

Figure 1. Solar PV accumulative installation projection till 2030 and 2050 [5].

Saudi Arabia has set a target of producing 58.7 gigawatts of renewable energy by 2030, comprising 40 GW from solar PV, 16 GW from wind energy, and 2.7 GW from concentrated solar power (CSP) [6–8], as illustrated in Figure 2. Thus, its commitment to renewable energy development could serve as a model for other countries seeking to transition to clean energy. The Kingdom of Saudi Arabia has a diverse topographical position, and therefore the exploration of RETs is of interest; for instance, due to the abundance of sunlight, it is an ideal location for solar energy production [9,10].

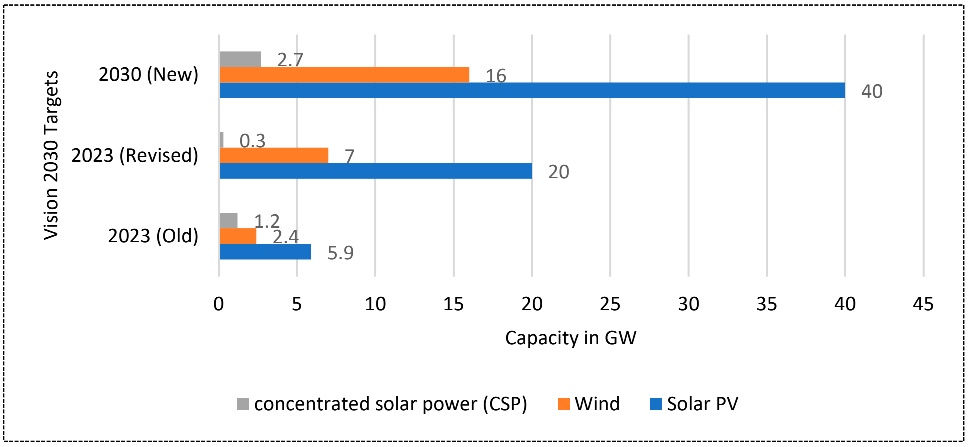

Figure 2. KSA Vision 2030's revised renewable targets [6].

Saudi Arabia has taken significant strides towards achieving its solar photovoltaic (PV) targets through a series of measures that include large-scale projects, policy frameworks, and initiatives. Two of the most notable large-scale solar projects are the Sakaka solar PV project and the Sudair solar PV project. The Sakaka solar PV project is located in the Al-Jouf region of Saudi Arabia and has a total capacity of 300 MW [11,12], whereas the Sudair solar PV project, located in Riyadh, has a capacity of 1.5 GW [13,14].

In the global context, Saudi Arabia's focus on renewable energy development and its emphasis on solar PV technology could have far-reaching implications. As the world seeks to transition away from fossil fuels and towards cleaner sources of energy, countries with favorable conditions for solar energy production, such as Saudi Arabia, could play a key role in driving the growth of the global solar industry.

This research article presents an analysis of the progress made in the deployment of solar photovoltaic (PV) energy in Saudi Arabia, highlighting the country's ambitious targets and the policies and initiatives that have facilitated the growth of the PV sector in recent years. This study provides insights into the challenges and opportunities of transitioning to a sustainable energy future in the KSA, historically dominated by fossil fuels, and contributes to the emerging literature on renewable energy adoption for sustainable development in any country.

The manuscript is divided into three main parts covering (i) KSA's demographic and electricity demand growth, (ii) the evolution of KSA's electricity sector, and (iii) sustainable renewable energy development. In Section 2, we discuss the correlation between population growth and energy demand, while Section 3 provides an overview of the evolution of KSA's electricity sector from the early 1960s to current modernization plans and Vision 2030. In Sections 4 and 5, we analyze the current state of renewable energy technology (RET) deployment in the Kingdom of Saudi Arabia, including the policies, regulations, and standards adopted for successful development and deployment. Finally, in Section 6, we draw observations based on the relevant literature to assess whether the KSA is making sufficient progress towards meeting its Vision 2030 renewable energy targets.

2. An Overview of the Kingdom of Saudi Arabia's Demographics

Saudi Arabia is the 12th largest country in the world, with a total area of 2,149,690 km^2 [15], and ranks 41st in the list of most populous countries of the world [16]. Its population increased from 3.55 million to 34.14 million from 1955 to 2019, as depicted in Figure 3. According to the General Authority of Statistics, in 2018, KSA's total population including expats reached 33.413660 million (Saudi national = 20.768627 million and non-Saudi = 12.645033 million) [17].

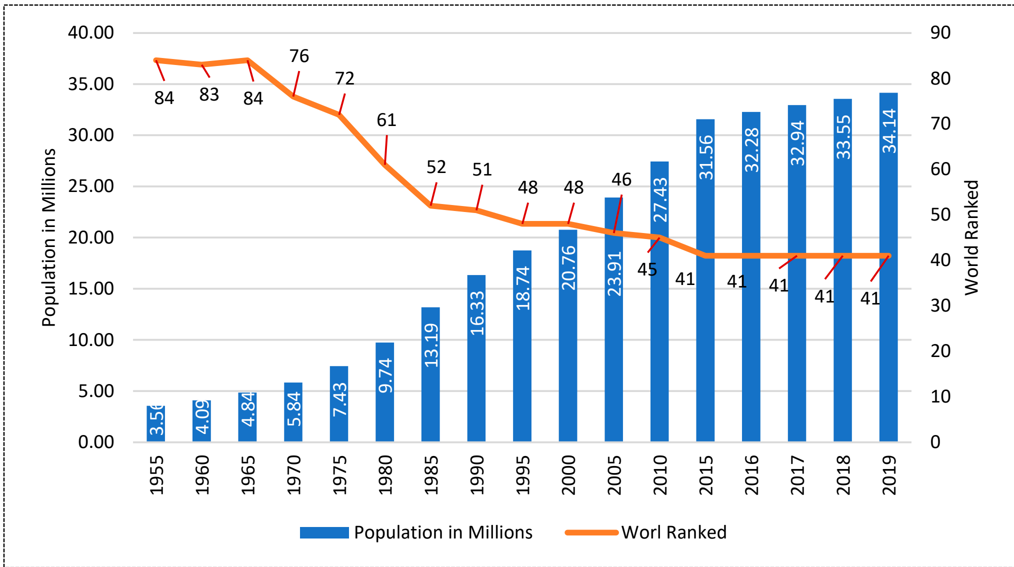

Figure 3. Saudi Arabia's population and world raking (during 1955–2019).

The relationship between population growth and electricity consumption growth is widely recognized as being directly proportional, with empirical evidence supporting this assertion [18,19]. This can be attributed to the fact that an increase in the number of people within a given area or region results in a corresponding rise in the demand for energy to support various economic activities, such as household energy consumption, industrial production, and transportation. As a consequence, there is a need to develop additional power generation and distribution infrastructure to meet the growing demand, which can have significant environmental and economic implications [20].

Saudi Arabia, like many other countries, has experienced significant population growth over the past few decades, which has corresponded with a marked increase in electricity consumption, as depicted in Figure 4. The country's electricity demand has more than doubled since 2000, driven by rapid economic growth and urbanization, among other factors. To address this challenge, the Saudi government has launched its Vision 2030 initiative, which seeks to diversify the country's economy, reduce its dependence on fossil fuels, and increase its reliance on renewable energy sources [21].

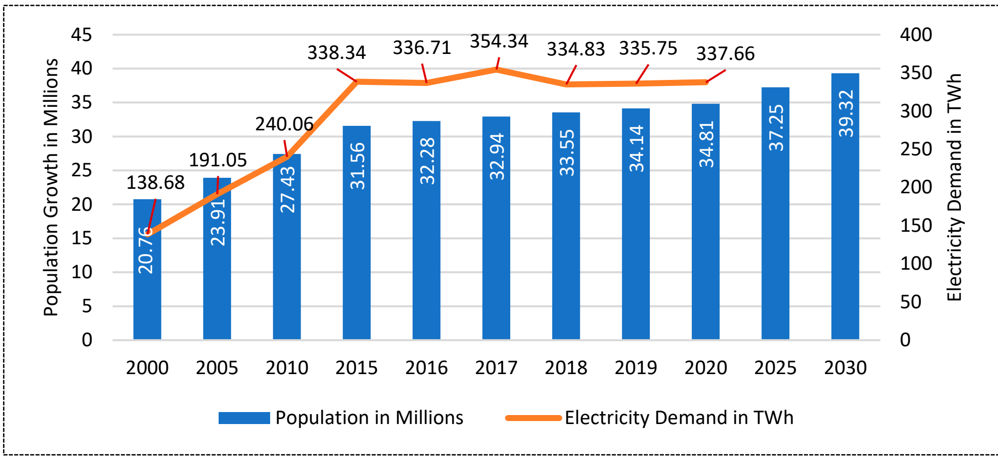

Figure 4. Population vs. electricity demand growth in Saudi Arabia.

The shift towards renewable energy in Saudi Arabia is not only driven by the need to meet growing electricity demand but also by broader economic and environmental considerations. By investing in renewable energy, the country can reduce its reliance on fossil fuels and diversify its economy while also mitigating the adverse impacts of climate change. Moreover, the deployment of renewable energy technologies can create new job opportunities and stimulate innovation in the energy sector [22].

3. Saudi Arabia's Electricity Sector Revolution

The role of energy is crucial for the progress of any nation and for supporting various socioeconomic endeavors. In the KSA, the electricity sector has undergone three distinct phases. The first phase dates back to the early 1960s, followed by the second phase from the late 1960s until the early 2000s, and finally the modern phase, marked by the deployment of renewable energy power plants from 2010 onwards, as illustrated in Figure 5.

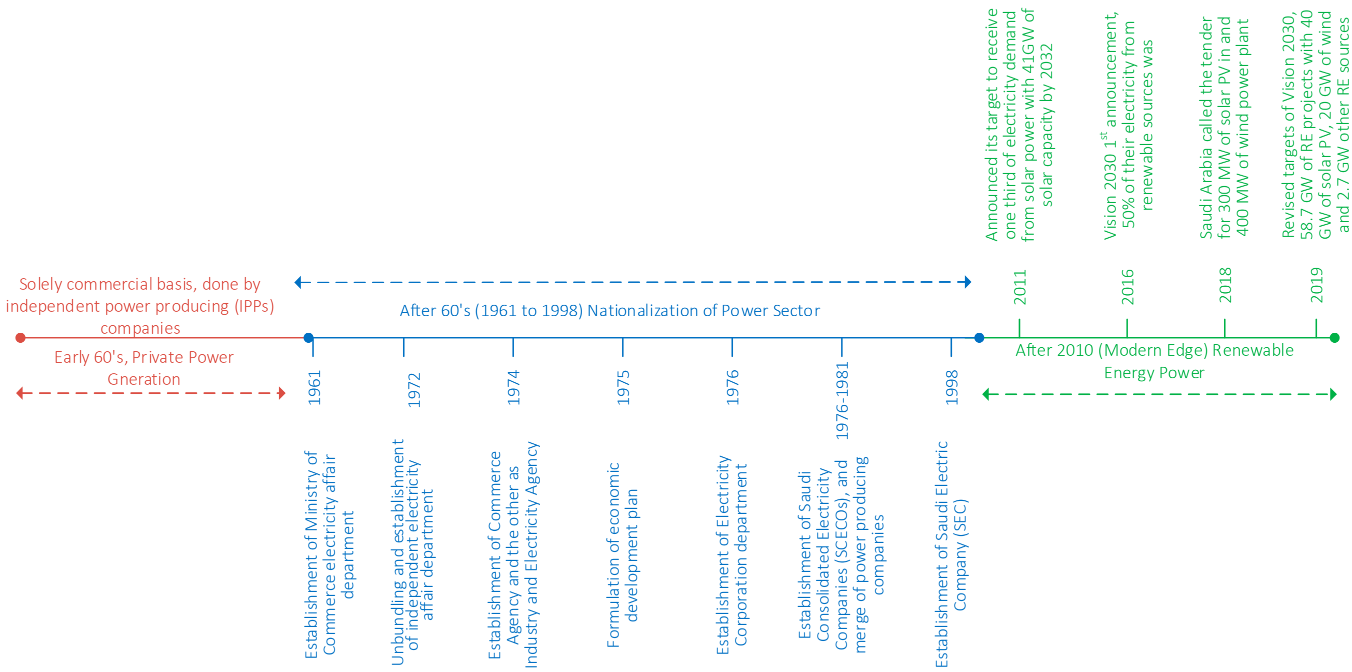

Figure 5. Kingdom of Saudi Arabia's electricity sector revolution.

3.1. Phase 1 (the Early 1960s)

In the early 1960s, prior to the establishment of KSA's development plans aimed at expanding the country's electricity infrastructure, independent power-producing (IPP) companies were solely responsible for the generation and transmission of electricity on a commercial basis. These companies operated with varying tariffs depending on the cost of production and provided electricity to towns and villages throughout Saudi Arabia.

3.2. Phase 2 (after the 1960s)

In 1961 (1381 AH), the Ministry of Commerce in Saudi Arabia established a dedicated department for electricity affairs. The department's primary objective was to develop comprehensive regulations and guidelines for the country's electricity sector. This included the oversight of private electricity generation, transmission, and distribution systems, as well as the licensing and permitting of national and independent power producers.

In 1972 (1392 AH), the Department of Electricity was founded as an independent state agency, after separating from the Ministry of Commerce. Its initial responsibility was to monitor and supervise the operations of both national and independent power-producing (IPP) companies. However, the department's scope was later expanded to include the planning of the future electrical infrastructure for the Kingdom of Saudi Arabia, covering the entire nation.

During 1974 (1394 AH), the Ministry of Commerce underwent a division resulting in the creation of two distinct agencies: the Commerce Agency and the Industry and Electricity Agency. Additionally, in that year, a decision was made to establish the electricity tariff for both national and independent power-producing (IPP) companies at a rate lower than their actual costs.

In the year 1975 (1395 AH), the Kingdom of Saudi Arabia devised a comprehensive economic development plan that emphasized investing in the electrification and industrial sectors. To execute this plan effectively, the Ministry of Industry and Electricity was established, comprising two subagencies: the Electricity Affairs Agency and the Industrial Affairs Agency. The former was tasked with coordinating and regulating the electrical sector, ensuring optimal planning and regulatory services.

In 1976 (1396 AH), the formation of the Electricity Corporation department aimed to synchronize the electricity strategies integrated into the Development Plan of the Kingdom.

During the years 1976 to 1981 (1396–1401 AH), Saudi Arabia merged all of its national and independent power-producing (IPP) companies into Saudi Consolidated Electricity Companies (SCECOs) in a gradual process. The SCECOs were divided into four regions—central, eastern, southern, and western—and were responsible for the entire electricity system of the country. They were also responsible for providing electricity to rural areas that were not previously covered by the consolidated companies. With the establishment of SCECOs and a well-planned development strategy, Saudi Arabia was successful in bringing electricity to all towns, villages, and settlements throughout the country.

In 1998 (1418 AH), a significant merger took place that led to the establishment of the Saudi Electric Company (SEC). This new entity brought together all the independent power-producing (IPP) companies operating within the Kingdom of Saudi Arabia. Presently, the SEC holds the responsibility of planning, coordinating, and providing regulatory services for electricity generation, transmission, and distribution throughout the country.

3.3. Phase 3 (Modern Edge—Renewable Energy Power Generation)

Starting in 2010 and continuing into the future, the increasing cost of oil has brought greater significance to the adoption of renewable energy for power generation in Saudi Arabia. In 2012, during the United Nations Climate Change Conference held in Qatar, Saudi Arabia declared its objective of achieving a significant share of its electricity supply from solar energy, with an ambitious target of 41 GW of solar capacity by 2032, which amounts to one-third of the country's total electricity demand [23].

On 7 June 2016, the newly appointed Minister of Energy, Industry, and Mineral Resources revealed a revised vision for Saudi Arabia's future energy mix, with a target of generating 10% of its power from renewable sources by 2030. This was a significant departure from the previous target of 50% renewable energy generation.

In the year 2018 (corresponding to 1439 AH), the Renewable Energy Project Development Office (REPDO) of Saudi Arabia issued a tender for the construction of a 300 MW solar PV plant in the location of "Sakaka" and a 400 MW wind power plant in "Dumat Al-Jandal". In the following year of 2019, twelve pre-developed projects, consisting of solar PV and wind power plants with a combined capacity of 3.1 GW, were presented for tender.

In 2019, the REPDO significantly revised its targets for Vision 2030. This included an ambitious increase from 9.5 GW to 27.3 GW of renewable energy capacity by 2023, with a long-term goal of 58.7 GW of renewable energy projects by 2030. Specifically, the plan called for 40 GW of solar PV, 16 GW of wind, and 2.7 GW of other renewable energy sources to be installed by 2030.

4. Saudi Arabia's Current Electricity Status

Over the past 40 years, Saudi Arabia has undergone significant development. This has led to a substantial surge in the demand for electricity [24]. Notably, the demand for electricity in the KSA has risen from 53.8 GW in 2013 to 64.16 GW in 2021. Projections indicate that by 2025, the power generation capacity in the KSA will reach 101 GW, and by 2030, it will increase to 109.6 GW. This growth will be accompanied by an increase in peak load demand from 68.5 GW in 2025 to 71.79 GW in 2030 [25], as depicted in Figure 6.

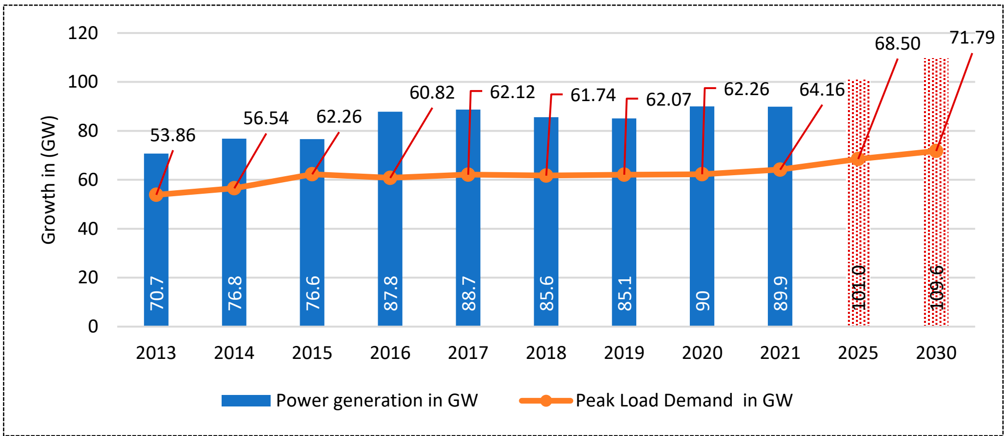

Figure 6. Power generation vs. demand (GW) of Saudi Arabia.

In pursuit of long-term economic prosperity, the Kingdom of Saudi Arabia acknowledges the importance of a diversified energy mix, including the incorporation of renewable energy sources [26]. To achieve this goal, the Ministry of Energy, Industry, and Mineral Resources has made a commitment to promote and implement renewable energy technologies under the National Transformation Program (NTP) and the National Renewable Energy Program (NREP). Their aim is to assume a leading role in meeting the country's future electricity demand, with a target of reaching 27.3 GW of renewable energy capacity by 2023 as part of the Vision 2030 initiative.

The Renewable Energy Project Development Office (REPDO) of Saudi Arabia invited bids in 2018 for the installation of a 300 MW solar PV plant in "Sakaka" and a 400 MW wind power plant in "Dumat Al-Jandal" [27]. In 2019, a total of eleven solar PV and one wind energy projects, which had already been pre-developed, were proposed and tendered. These projects have a combined capacity of 3.075 GW, as shown in Figure 7.

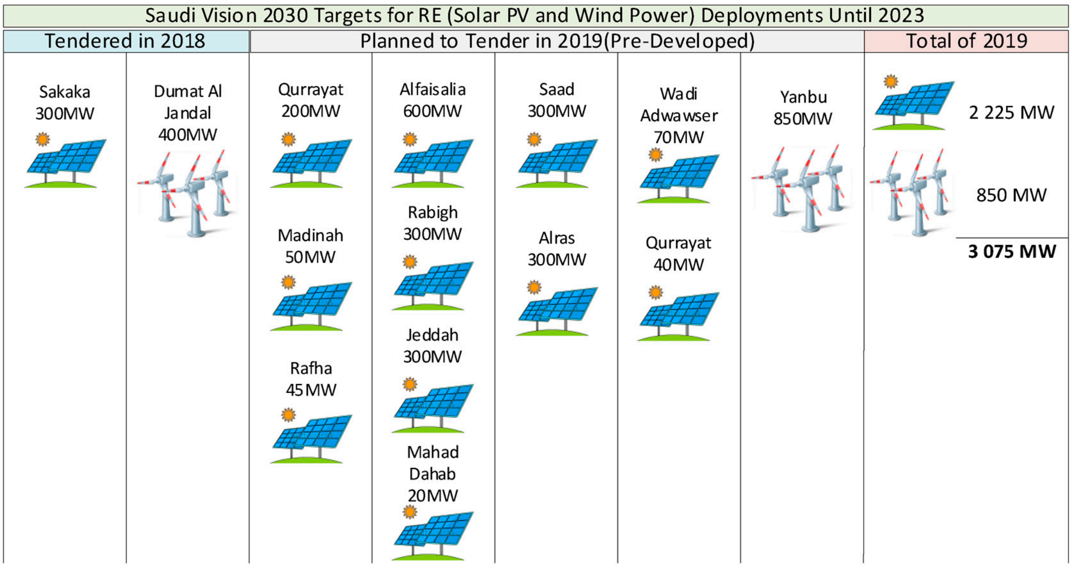

Figure 7. Saudi Vision 2030 targets for RE (solar PV and wind power) deployment.

On 28 January 2019, as part of its efforts to expand its renewable energy capacity, the Renewable Energy Project Development Office (REPDO) announced that it was inviting expressions of interest (EOIs) for the development of seven solar PV projects. These projects were part of a larger set of 12 pre-developed renewable energy power projects. The seven tendered solar PV projects had a combined potential capacity of 1.515 GW and were located in different regions across the Kingdom of Saudi Arabia, as shown in Figure 8. These projects were aimed at increasing the country's renewable energy capacity and reducing its reliance on fossil fuels [28].

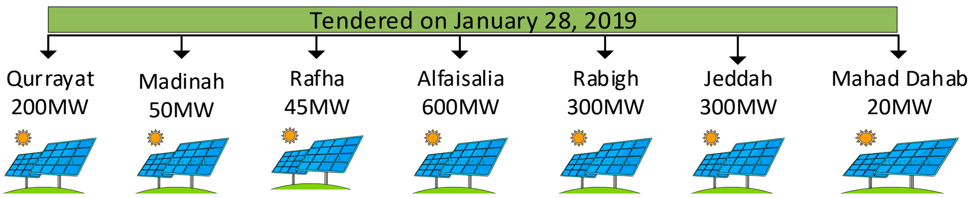

Figure 8. The solar power plants tendered in 2019.

The EOI solicitation invited companies to submit their interest in developing, designing, permitting, engineering, financing, procuring, constructing, commissioning, testing, completing, owning, insuring, operating, and maintaining these seven solar PV projects.

The objective of these projects was to establish long-term power purchase agreements (PPAs) with the Saudi Power Procurement Company (SPPC). This would help the country to achieve its target of generating 58.7 GW of renewable energy by 2030, as part of its Vision 2030 plan.

Since then, there have been significant developments in the renewable energy sector in Saudi Arabia. The country has successfully implemented several renewable energy projects, including wind and solar projects, and has attracted major international players in the renewable energy industry.

In fact, in 2021, the country announced its intention to invest USD 50 billion in renewable energy projects over the next decade. This investment is expected to result in a significant increase in the country's renewable energy capacity, which is currently dominated by oil and gas.

In addition to the aforementioned projects, The Kingdom has also planned to deploy 35+ renewable energy parks throughout the Kingdom, as depicted in Figure 9.

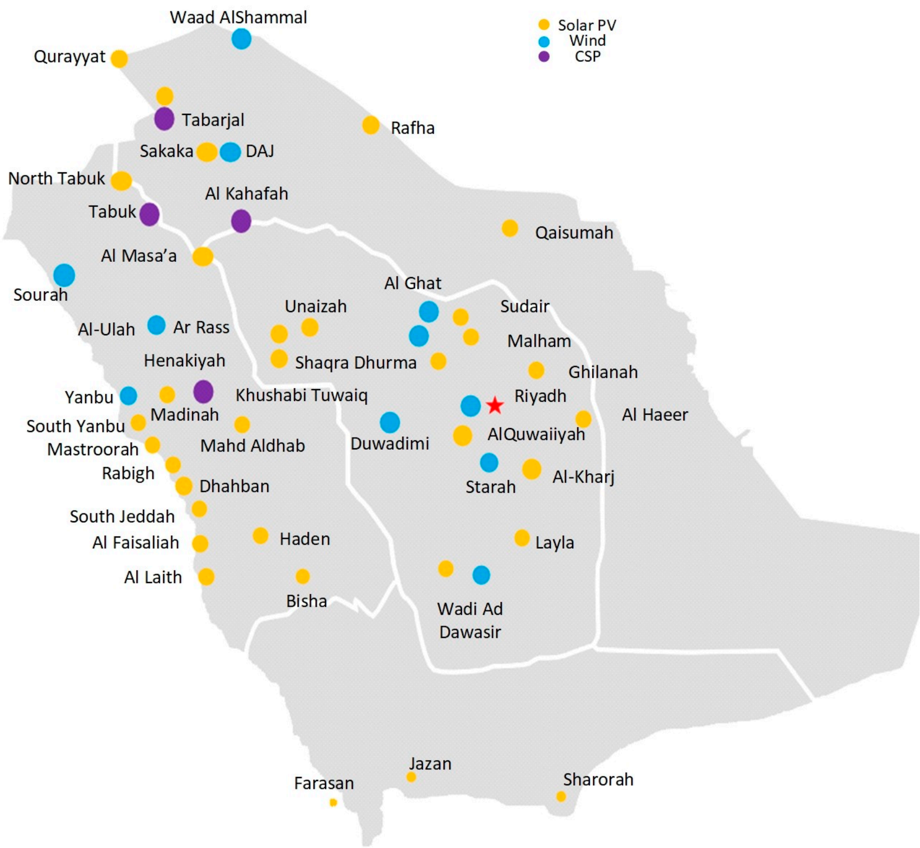

Figure 9. KSA Vision 2030's renewable energy parks [28].

4.1. Large-Scale Solar Projects in Saudi Arabia

4.1.1. Sakaka Solar PV Project

The Sakaka solar PV project is one of the first large-scale commercial solar projects located in Sakaka, Al-Jouf Province of Saudi Arabia. The Sakaka solar PV project is part of Saudi Arabia's Vision 2030 initiative, which aims to reduce the country's dependence on fossil fuels and increase its renewable energy capacity to 58.7 GW by 2030 [9,11,29,30]. This project also supports the Kingdom's efforts to diversify its economy and reduce its carbon footprint.

The project was awarded to the consortium led by ACWA Power, a Saudi-based company that is specialized in developing and operating power and water projects. The Sakaka solar PV project has a capacity of 300 MW and covers an area of 6 square kilometers.

- The Sakaka solar PV project has a 25-year power purchase agreement (PPA) with the Saudi Power Procurement Company (SPPC). The PPA includes a tariff rate of 0.08872 SAR/kWh (USD 0.024/kWh), which is one of the lowest solar tariff rates in the world. The low tariff rate was achieved due to the competitive bidding process used by the REPDO, which attracted bids from several international companies.
- The Sakaka solar PV project was built with the aim of reducing Saudi Arabia's dependence on oil and gas for electricity generation and diversifying the country's energy mix. The project is expected to produce around 680 GWh of electricity annually, which is enough to power around 75,000 homes.

4.1.2. Sudair Solar PV Project

The Sudair solar PV project is a 1.5 GW photovoltaic power plant under development in the Sudair Industrial City in Saudi Arabia and is expected to be one of the largest solar power plants in the world. The Sudair solar PV project is part of Saudi Arabia's plan to increase its solar PV capacity to 40 GW by 2030 [31–34].

- The Sudair solar PV project has a 25-year power purchase agreement (PPA) with the SPPC, with a tariff rate of 0.060 SAR/kWh (USD 0.016/kWh). This is one of the lowest tariff rates for solar energy in the world and was achieved through a competitive bidding process.
- The project is part of Saudi Arabia's Vision 2030 plan, which aims to diversify the country's economy and reduce its dependence on oil by increasing the share of renewable energy in its energy mix. The Sudair solar PV project is expected to generate around 2.9 TWh of electricity annually, which is equivalent to the energy needs of around 185,000 households in Saudi Arabia.

The Sakaka and Sudair solar PV projects are an important step towards achieving Saudi Arabia's renewable energy goals and reducing the country's dependence on fossil fuels. These projects are supported by a range of policies and regulations that help to reduce the cost of developing renewable energy projects and facilitate their integration into the country's energy mix.

4.1.3. Policy and Regulatory Support for Large-Scale Solar PV System

- **Power Purchase Agreement**: Both Sakaka and Sudair solar PV projects have a 25-year power purchase agreement (PPA) with the Saudi Power Procurement Company (SPPC). The PPA guarantees a fixed price for the electricity generated by the project, which provides a stable revenue stream for the project developer and reduces the risk associated with investing in renewable energy.
- **Regulatory Framework**: The Saudi government has developed a regulatory framework to support the development and integration of renewable energy into the country's energy mix. This framework includes regulations for interconnection, grid access, and renewable energy certificates, which help to facilitate the integration of renewable energy into the grid.
- **Incentives**: The Saudi government offers incentives for companies that invest in renewable energy, including tax exemptions and reduced fees for land use and permits. These incentives help to reduce the cost of developing renewable energy projects and encourage more companies to invest in the sector.

4.2. Solar Energy Data Collection in Saudi Arabia—A Historical Brief

In the early 1960s, the first PV System in Saudi Arabia was installed by a French Company at "Madinah Al Munawrah" airport [35,36]. Initially, it was a small beacon and then converted into a small research project in 1969. In 1977, the King Abdullah City for Science and Technology (KACST) was established for the research and development (R&D) and promotion of renewable energy technologies, specifically solar PVs, in the Kingdom of Saudi Arabia. Therefore, that small systematized beacon project was undertaken by the KACST for further R&D [37–39]. After the establishment of King Abdullah City for Science and Technology, the first ever-large sale R&D project for renewable resource monitoring and mapping (RRMM) in the Kingdom of Saudi Arabia was the "Atlas Project" in 1994. It was a joint project by the Energy Research Institute (ERI) of KACST, KSA, and the National Renewable Energy Laboratories (NREL), USA. Initially, in the RRMM project, twelve stations were installed for solar data collection, specifically for the measurement of solar irradiation (IRR) [40], which are shown in the map in Figure 10.

Over time, the ERI and NREL extended their RRMM data collection stations from twelve to fifty-four until 2018, as shown in the map in Figure 11. All the data collection stations collect data, including humidity, temperature, wind speed direction, and barometric pressure, for three components of solar PV systems with one-minute resolution [41].

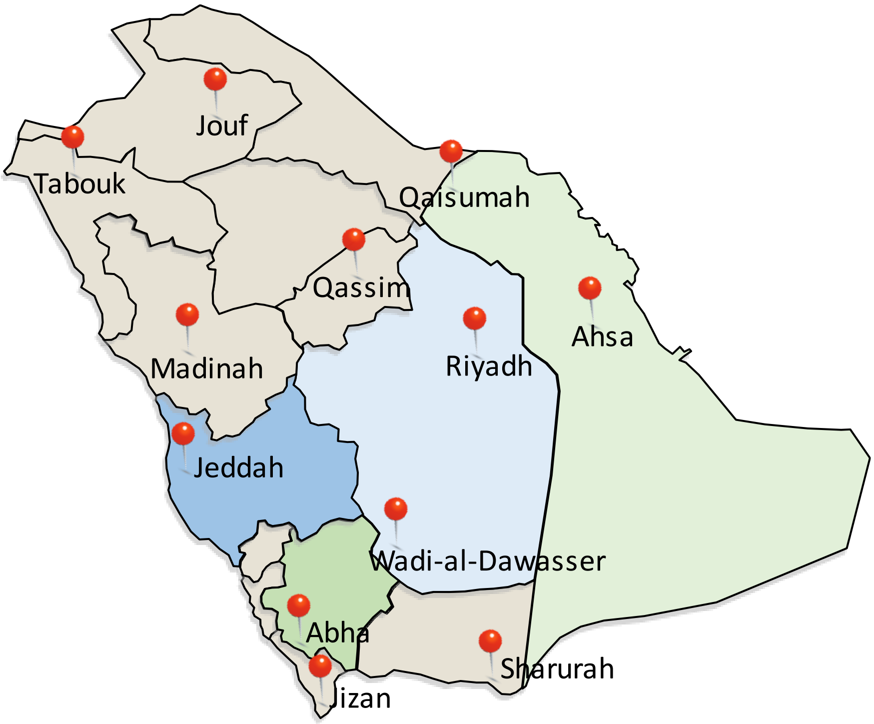

Figure 10. The solar data collation stations of Atlas 1994 in the KSA.

Figure 11. Renewable Resource Atlas: RRMM solar data collection stations in the KSA [42].

The KSA Solar Radiation Atlas provides evidence that Saudi Arabia has exceptional direct normal irradiance (DNI). The DNI levels in Saudi Arabia are consistently high, with a minimum of 24 MJ/m^2/day and a maximum of 30 MJ/m^2/day, establishing its potential to be one of the world's most advanced solar-energy-based technology nations [43,44], as seen in Figure 12.

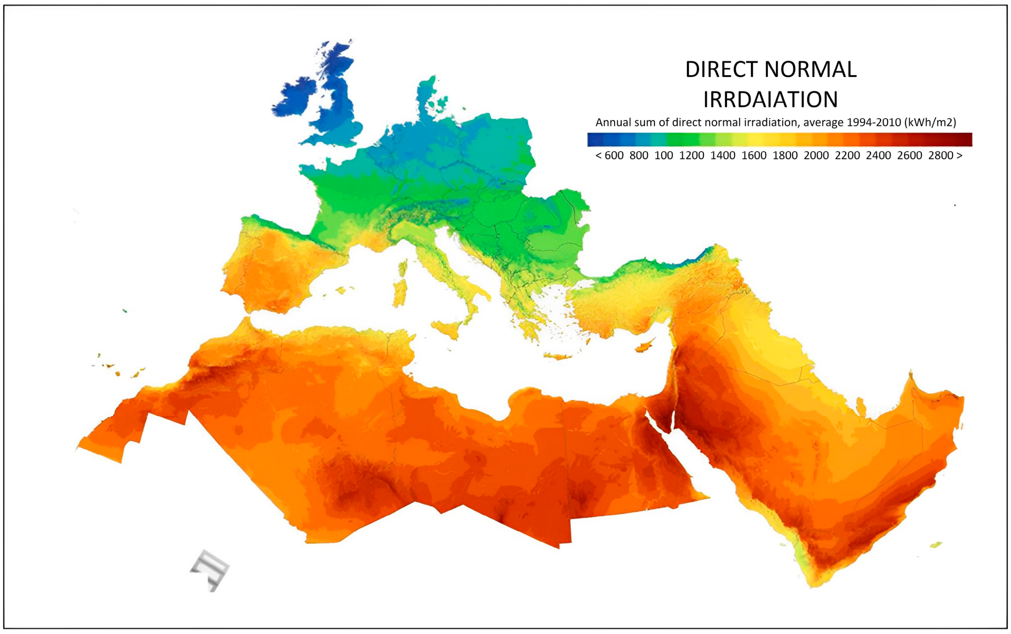

Figure 12. EU and MENA region's solar map [43].

5. Renewable Energy Policies in Saudi Arabia

As the world undergoes energy system transformations, policymakers are increasingly focusing on developing and implementing technologies that can integrate renewable energy sources. Among these sources, solar photovoltaic and wind power plants have become crucial. The Kingdom of Saudi Arabia (KSA) is also seeking alternative energy sources to reduce the negative impacts of heightened fossil fuel consumption. To achieve this goal, the country has implemented policies aimed at promoting the adoption of renewable energy technologies (RETs), deploying distributed energy resources (DERs), and fostering innovation in relevant technological fields. These policies aim to reduce greenhouse gas emissions, ensure energy security and independence, and meet the growing demand for electricity [9,45].

In line with the announcement of Vision 2030, which includes the installation of 40 GW of solar PV and a total of 58.7 GW including from other renewable energy sources, KSA policymakers have been actively promoting renewable energy through various measures such as renewable energy targets, supportive regulations, public financing, and fiscal incentives. However, compared with leading countries such as China, the USA, India, and Germany, the KSA has lagged in adopting effective renewable energy policy instruments to drive renewable energy technology development and deployment, as shown in Table 1.

In 2009, the Electricity and Cogeneration Regulatory Authority (ECRA), currently renamed Water and Electricity Regulatory Authority (WERA), took the first step towards developing the National Renewable Energy Policy for Saudi Arabia. The proposed policy aimed to promote energy source diversification; enhance energy supply to remote regions while mitigating associated costs; generate employment opportunities; encourage the localization of renewable energy equipment manufacturing to boost technical advancement within the country; foster competition within the renewable energy sector; optimize economies of scale to reduce renewable energy costs; ensure policies, regulations, and procedures do not impede the development of renewable energy; and establish stable and attractive investment prospects for renewable energy [46,47].

Table 1. RE policies in different countries, including KSA—a comparative analysis [6].

Country	Renewable Energy Targets	Renewable Energy	Regulatory Policies							Fiscal Incentives and Public Financing			
			Feed-in Tariff/ Premium Payment	Electric Utility Quota Obligation/ RPS	Net metering/ Billing	Transport Obligation/ Mandate	Heat Obligation/ Mandate	Tradable REC	Tendering	Investment or Production Tax Credits	Reductions in Sales, Energy, CO^2, VAT or Other Taxes	Energy Production Payment	Public Investment, Loans, Grants, Capital Subsidies or Rebates
United States	P ◊		□	□ ◊	□ ◊	•	□	□	◦	•	•		• ◊
United Kingdom	E, P, T, HC		• ◊	•		•		•	○		•	•	•
Germany	E, P, HC, T		• ◊			•	•	•	○	•	•		• ◊
Canada	P	•	□ ◊	□	□	•			◦	•	•		•
China	E ◊, P, HC	•	• ◊	•		□	•		•	•	•	•	•
India	P, HC	•	□ ◊	•	□ ◊	□ ◊	□	•	○	•	•	•	•
Saudi Arabia	P	•			•				•				

E = energy (final or primary); P = power; HC = heating or cooling; T = transport; • existing national policy or tender framework (could include subnational); □ existing subnational policy or tender framework (but not national); ○ national tender; ◦ Subnational tender; ◊ New.

Saudi Arabia has been making significant strides towards increasing its share of renewable energy in the national energy mix. To this end, rooftop solar PV systems are a promising technology for Saudi Arabia, especially in remote and off-grid areas. The following initiatives are some of the policies and incentives developed for rooftop solar PV systems in Saudi Arabia:

- **Net Metering**: In 2018, the Saudi Electricity Company (SEC) implemented net metering, a policy that incentivizes homeowners to install rooftop solar PV systems by allowing them to sell any excess electricity back to the grid for credit. Residential off-takers are offered a rate of 7 halalas/kWh for any surplus electricity they export, while all non-residential off-takers (such as commercial, industrial, agricultural, and governmental entities) are offered a rate of 5 halalas/kWh for their surplus electricity exports to the utility grid. This policy is beneficial in reducing electricity bills for homeowners and promoting the adoption of solar PV systems in the country [48,49].
- **Soft loans**: The Saudi Industrial Development Fund (SIDF) provides soft loans to individuals and companies for the purchase and installation of distributed power generation systems (rooftop solar PV systems). These loans have low interest rates and flexible repayment terms, making it easier for homeowners and businesses to invest in renewable energy [50].

In Saudi Arabia, there are currently two notable policies and incentives enacted to promote the adoption of rooftop solar PV systems. These measures are designed to encourage homeowners and businesses to invest in renewable energy, reduce their energy bills, and contribute to the country's sustainable development goals.

In 2017, the Electricity and Cogeneration Regulatory Authority (ECRA) established a new set of guidelines to allow electricity consumers to generate and export their own energy using small-scale solar photovoltaic systems. The ultimate goal of these regulations is to promote the integration of these systems into the national distribution network while ensuring their safe and efficient design, implementation, upkeep, and operation across Saudi Arabia. Figure 13 highlights the prerequisites and criteria for small-scale solar PV systems in the country [51].

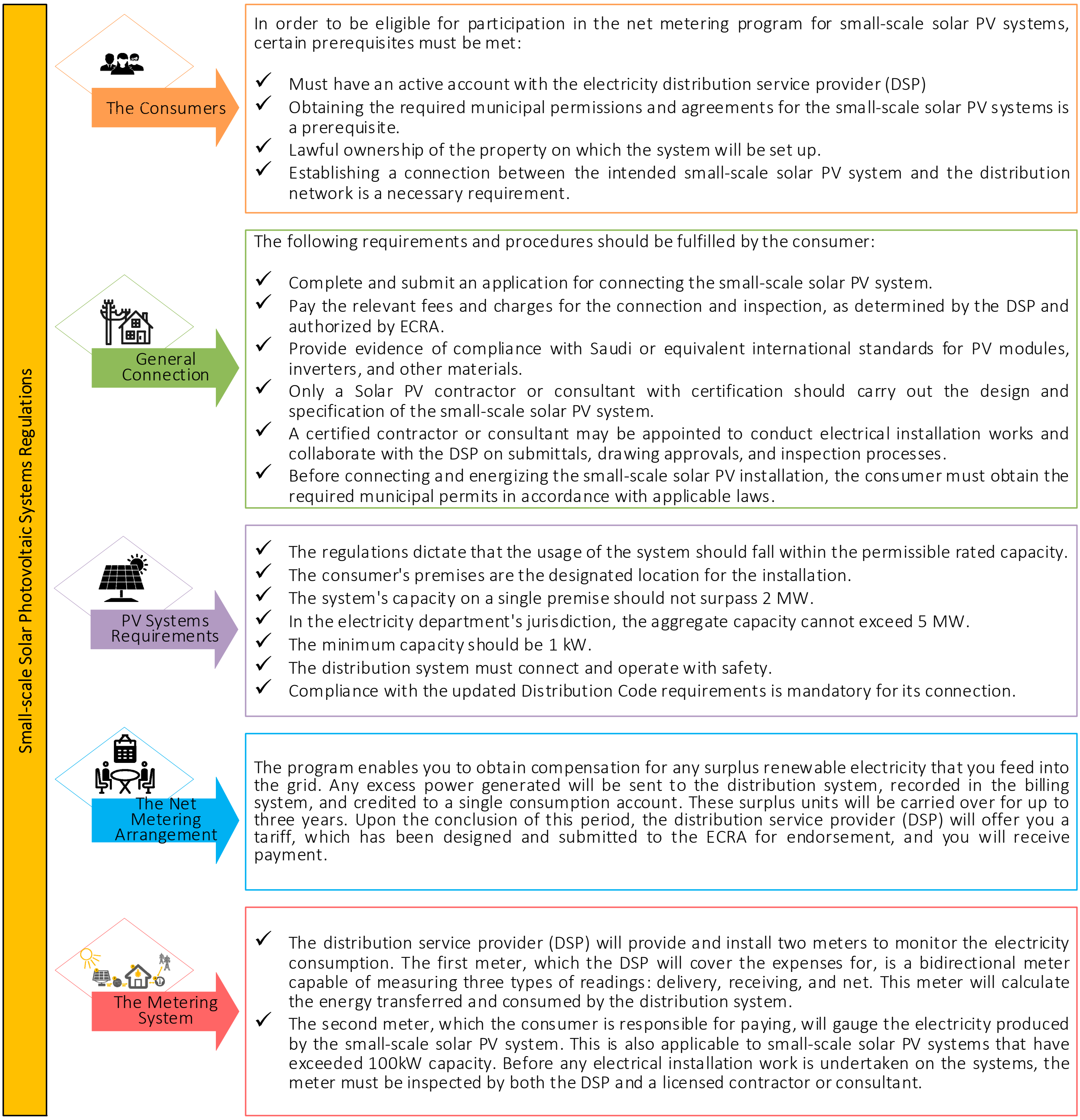

Figure 13. Summary of applications and conditions for PV systems' installation in the Kingdom of Saudi Arabia.

To further simplify the process of installing these systems in Saudi Arabia, the Saudi Electric Company (SEC) has issued a standard called the "Technical Standards for the Connection of Small-Scale Solar PV Systems to the LV and MV Distribution Networks of SEC." This standard sets a universal set of prerequisites for small-scale solar PV systems that will work in conjunction with the LV and MV distribution networks of the Saudi Electricity Company (SEC) throughout the country [52]. The goal is to promote the sustainable integration of renewable energy sources such as solar PV. The standard also establishes specific criteria [53], including the following features:

1. To maintain stable frequency and voltage in the power system during disturbances, certain criteria are mandated by the standard;
2. Specific criteria for the start, operation, and stoppage of small-scale solar PV systems are mandated by the standard;
3. In order to avoid any disruptions or harm to the distribution network and other connected customers, specific requirements are in place for small-scale solar PV systems;
4. The standard requires certain prerequisites to prevent small-scale solar PV systems from operating with any section of the distribution network that has intentionally been disconnected from the primary power system.

In order to achieve the Saudi Arabia Vision 2030 target of 40 GW for solar PV, a variety of procedures, codes, regulations, and standards have been put in place to aid in the successful implementation and development of solar PV technologies in the Kingdom. A comprehensive list of all the solar-PV-related regulations, standards, codes, and procedures is provided in Tables 2 and 3, respectively.

Table 2. List of regulations, standards, and codes related to renewable energy development in Saudi Arabia.

Document	Type			Organization	Year	Status		
	Regulation	Standard	Code			Enforce	Proposed	Expired
Small-Scale Solar PV Systems Regulations [54]	√			Electricity and Cogeneration Regulatory Authority	2017	√		
Technical Standards for the Connection of Small-scale Solar PV Systems to the LV and MV Distribution Networks of SEC [52]		√		Saudi Electricity Company	2018	√		
The Electricity Law [55]	√			Electricity and Cogeneration Regulatory Authority	2007	√		
The Saudi Arabian Distribution Code [56]			√	Saudi Electricity Company	2011	√		
Saudi Arabian Grid Code [57]			√	National Grid Saudi Arabia	2017	√		
The Saudi Building Code Electrical Requirements [58]			√	Saudi Building Code National Committee	2007	√		

Note: This list is a compilation of policies, regulations, standards, and codes as provided by the respective organization. It is important to note that these documents are subject to future revisions, amendments, or extensions. To ensure the most up-to-date information is being utilized, it is the responsibility of the user to obtain and refer to the latest published versions.

Table 3. List of standards adopted by the SASO for renewable energy development in the Kingdom of Saudi Arabia.

Standard Type	Standard No.	Standard Level		Organization		
		National	International	SASO	IEC	EN
Terrestrial photovoltaic (PV) modules—Design qualification and type approval—Part 1: Test requirements [59].	SASO IEC 61215-1:2017	√	√	•	•	
Terrestrial photovoltaic (PV) modules—Design qualification and type approval—Part 1-1: Special requirements for testing of crystalline silicon photovoltaic (PV) modules [60].	SASO IEC 61215-1-1:2017	√	√	•	•	
Terrestrial photovoltaic (PV) modules—Design qualification and type approval—Part 1-2: Special requirements for testing of thin-film cadmium telluride (CdTe)-based photovoltaic (PV) modules [61].	SASO IEC 61215-1-2:2017	√	√	•	•	

Table 3. *Cont.*

Standard Type	Standard No.	Standard Level		Organization		
		National	International	SASO	IEC	EN
Terrestrial photovoltaic (PV) modules—Design qualification and type approval—Part 1-3: Special requirements for testing of thin-film amorphous silicon-based photovoltaic (PV) modules [62].	SASO IEC 61215-1-3:2017	√	√	•	•	
Terrestrial photovoltaic (PV) modules—Design qualification and type approval—Part 1-4: Special requirements for testing of thin-film Cu(In,GA)(S,Se)2-based photovoltaic (PV) modules [63].	SASO IEC 61215-1-4:2017	√	√	•	•	
Terrestrial photovoltaic (PV) modules—Design qualification and type approval—Part 2: Test procedures [64].	SASO IEC 61215-2:2017	√	√	•	•	
Photovoltaic (PV) module safety qualification—Part 1: Requirements for construction [65].	SASO IEC 61730-1:2017	√	√	•	•	
Photovoltaic (PV) module safety qualification—Part 2: Requirements for testing [66]	SASO IEC 61730-2:2017	√	√	•	•	
Salt mist corrosion testing of photovoltaic (PV) modules [67].	SASO IEC 61701:2014	√	√	•	•	
Photovoltaic (PV) modules—Test methods for the detection of potential-induced degradation—Part 1: Crystalline silicon [68].	SASO IEC TS 62804-1:2017	√	√	•	•	
Photovoltaic (PV) modules—Ammonia corrosion testing.	SASO IEC 62716:2016	√	√	•	•	
Photovoltaic (PV) modules—Transportation testing—Part 1: Transportation and shipping of module package units [69].	SASO IEC 62759-1:2015	√	√	•	•	
Junction boxes for photovoltaic modules—Safety requirements and tests [70]	SASO IEC 62790:2015	√	√	•	•	
Connectors for DC application in photovoltaic systems—Safety requirements and tests [71].	SASO IEC 62852:2015	√	√	•	•	
Photovoltaic modules—Bypass diode—Thermal runaway test [72].	SASO IEC 62979:2018	√	√	•	•	
Terrestrial photovoltaic (PV) modules—Quality system for PV module manufacturing [73]	SASO IEC TS 62941:2017	√	√	•	•	
Photovoltaic (PV) modules—Cyclic (dynamic) mechanical load testing [74].	SASO IEC TS 62782:2017	√	√	•	•	
Environmental testing—Part 2-68: Tests—Test L: Dust and sand [75].	IEC 60068-2-68:1994		√	•	•	
Safety of power converters for use in photovoltaic power systems—Part 1: General requirements [76].	SASO IEC 62109-1:2017	√	√	•	•	
Safety of power converters for use in photovoltaic power systems—Part 2: Particular requirements for inverters [77].	SASO IEC 62109-2:2012	√	√	•	•	
Overall efficiency of grid-connected photovoltaic inverters [78].	EN 50530:2010		√			•
Data sheet and nameplate for photovoltaic inverters [79].	EN 50524:2009		√			•
Utility-interconnected photovoltaic inverters—Test procedure of islanding prevention measures [80].	SASO IEC 62116:2017	√	√	•	•	
Utility-interconnected photovoltaic inverters—Test procedure for low voltage ride-through measurements [81].	SASO IEC TS 62910:2017	√	√	•	•	
Photovoltaic power-generating systems—EMC requirements and test methods for power conversion equipment [82].	SASO IEC 62920:2018	√	√	•	•	
Electromagnetic compatibility (EMC)—Part 3-2: Limits—Limits for harmonic current emissions (equipment input current ≤16 A per phase) [83].	IEC 61000-3-2:2014		√		•	
Electromagnetic compatibility (EMC)—Part 3-12: Limits—Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and ≤75 A per phase [84].	IEC 61000-3-12:2011		√		•	
Electric cables for photovoltaic systems [85].	EN 50618:2014		√			•
Electric cables for photovoltaic systems with a voltage rating of 1.5 kV DC [86].	SASO IEC 62930:2018	√	√	•	•	
Electronic equipment for use in power installations [87].	EN 50178:1997		√			•
CSV Consolidated version—Safety requirements for power electronic converter systems and equipment—Part 1: General [88].	IEC 62477-1:2012		√		•	
Balance-of-system components for photovoltaic systems—Design qualification natural environments [89].	SASO IEC 62093:2008	√	√	•	•	
Low-voltage switchgear and control gear assemblies—Part 2: Power switchgear and control gear assemblies [90].	IEC 61439-2:2011		√		•	

SASO = Saudi Standards, Metrology, and Quality Organization, **IEC** = International Electrotechnical Commission, **EN** = European Standards. **Note:** The list encompasses SASO's standards that were in effect when this document was published. Nevertheless, it is crucial for users to locate and apply the most recent published versions, as standards are susceptible to modifications, amendments, or extensions in the future.

6. Observations

A renewable energy policy is a critical factor in the successful implementation of renewable energy as a reliable and cost-effective source of energy in any country. Renewable energy policies help provide the necessary framework and incentives to encourage investments in the sector, promote the adoption of clean energy technologies, and support the growth of the industry. These policies vary significantly depending on a range of factors, including the environmental conditions, political, economic, and social status of a country [91].

For instance, the energy policy in the United States aims to ensure the availability of secure, affordable, and dependable energy. To achieve this, the US government has implemented several programs and initiatives aimed at promoting the deployment of renewable energy technologies, including solar, wind, and geothermal energy. These policies have been effective in supporting the growth of the renewable energy industry in the US, which has seen significant investment and job creation in recent years.

On the other hand, the energy policy in the European Union (EU) focuses on energy security, affordability, and environmental sustainability. The EU has set ambitious targets for reducing greenhouse gas emissions, increasing the share of renewable energy in the energy mix, and improving energy efficiency. To achieve these targets, the EU has implemented several policies and regulations aimed at promoting the adoption of renewable energy technologies and reducing the dependence on fossil fuels.

Similarly, in the Kingdom of Saudi Arabia, several public sector organizations, including the Saudi Electric Company (SEC), the National Grid (NG), and the Water and Electricity and Cogeneration Regulatory Authority (WERA), have developed regulations, standards, and codes to promote and successfully deploy renewable energies, specifically solar photovoltaic. These policies have been effective in supporting the growth of the solar industry in Saudi Arabia, which has seen significant investment and job creation in recent years.

Additionally, the Saudi Standards, Metrology, and Quality Organization (SASO) has adopted nearly all of the international standards (IEC and EN) related to solar photovoltaics, as outlined in Tables 2 and 3. This adoption of international standards has helped create a level playing field for the industry and has facilitated the deployment of solar photovoltaic systems in Saudi Arabia.

Although the KSA has taken several measures to achieve its Vision 2030 targets, reaching these targets necessitates the formulation and establishment of an effective renewable energy policy framework that considers worldwide trends in renewable energy policy, particularly in leading countries, as highlighted in Table 1.

To improve its renewable energy policies, the KSA can learn from the experiences of these leading countries. For instance, feed-in tariffs, subsidies, and tax incentives are some of the policy instruments used in these countries to support the growth of the renewable energy sector. The KSA can adopt these policy instruments to encourage investments in the sector, promote the adoption of clean energy technologies, and support the growth of the renewable energy industry.

Developing a comprehensive and effective renewable energy policy is crucial for the KSA to achieve its Vision 2030 renewable energy targets. To achieve optimal results, it is essential to explore and analyze global trends in renewable energy policy, particularly those of leading countries. By doing so, the KSA can identify the most effective policy instruments and tailor them to its unique circumstances.

7. Conclusions

The progress of solar photovoltaic (PV) energy deployment in the Kingdom of Saudi Arabia (KSA) has been impressive in recent years, with the government's commitment to renewable energy development and the launch of large-scale solar projects such as the Sakaka solar PV project and the Sudair solar PV project. The KSA has also implemented policies and initiatives aimed at promoting the use of solar energy, including net metering programs and subsidies for residential solar PV installations.

This article provides an overview of the energy landscape in the KSA. The progress of solar PV deployment in the KSA was also discussed, with an emphasis on growth trends, capacity additions, and the role of policies and regulations in supporting the sector.

As the KSA aims to diversify its energy mix and reduce its dependence on fossil fuels, solar PV has emerged as a promising alternative. The country has a diverse topographical position that makes the exploration of renewable energy technologies (RETS) an area of interest, particularly solar energy production, due to the abundance of sunlight. KSA's focus on renewable energy development and its emphasis on solar PV technology could have far-reaching implications in the global context, as countries with favorable conditions for solar energy production could play a key role in driving the growth of the global solar industry.

To further support the growth of the solar PV sector in the KSA, it is recommended that the government continues to invest in large-scale solar projects, such as the construction of utility-scale PV plants. Additionally, the government could provide incentives for private investment in solar PV projects and further develop policies to encourage the adoption of rooftop solar PV systems in residential and commercial sectors. It is also recommended that the KSA continues to invest in grid infrastructure and technology, including battery storage systems and smart grid solutions, to support the integration of solar PV into the national grid.

Overall, the progress of solar PV deployment in the KSA is a positive step towards achieving a sustainable future, and with continued investment and policy support, it has the potential to become a leader in renewable energy development.

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