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SOLAR ENERGY IN SAUDI ARABIA: CURRENT STATUS, CHALLENGES, AND STRATEGIC OPPORTUNITIES UNDER VISION 2030

ENERGIA SOLAR NA ARÁBIA SAUDITA: SITUAÇÃO ATUAL, DESAFIOS E OPORTUNIDADES ESTRATÉGICAS NO ÂMBITO DA VISÃO 2030

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Sulaman Rafiq*
***Department of Applied Science, Scientific Studies Squadron, King Faisal Air Academy (KFAA), Majma'ah, Saudi Arabia
srafiq@hotmail.com

The authors declare that there is no conflict of interest

Abstract
The Vision 2030 initiative by Saudi Arabia has redefined the role of solar energy from an obscure technology to an enabling technology for Saudi Arabia's energy, economic, and environmental security. This review article attempts to synthesize existing literature on solar energy in Saudi Arabia published between 2020 and 2025 to determine the status of solar energy in Saudi Arabia, the existing barriers to solar energy implementation, and the opportunities to support Saudi Arabia's Vision 2030. This review article adopts a PRISMA protocol [1] to review existing literature on utility-scale photovoltaic, distributed photovoltaic, concentrated solar power, desert performance, grid integration, and industrialization. The review of existing literature indicates that Saudi Arabia's national plans are geared towards the implementation of utility-scale photovoltaic, concentrated solar power, and the parallel commitment to increasing the share of renewable energy in the national energy mix to about half by 2030 [2, 3]. The review of existing literature indicates that project implementation has been expedited by competitive tendering and public-private partnerships, with flagship projects such as Sakaka and Sudair indicating Saudi Arabia's commitment to moving from targets to implementation [4, 16, 17]. The review of existing literature indicates that Saudi Arabia's solar energy performance is limited by factors such as desert-specific factors like dust storms, aerosol dimming, and module temperature, as well as solar energy system-specific factors like grid flexibility, permitting, bankability, and local supply chain readiness [20, 23, 24, 25]. The review of existing literature indicates that the next steps in Saudi Arabia's solar energy implementation are less about determining the feasibility of solar energy implementation and more about orchestrating reliable scale,

Resumo
A iniciativa Visão 2030 da Arábia Saudita redefiniu o papel da energia solar, transformando-a de uma tecnologia pouco conhecida em uma tecnologia essencial para a segurança energética, econômica e ambiental do país. Este artigo de revisão busca sintetizar a literatura existente sobre energia solar na Arábia Saudita, publicada entre 2020 e 2025, a fim de determinar o estado atual da energia solar no país, as barreiras existentes à sua implementação e as oportunidades para apoiar a Visão 2030 da Arábia Saudita. Este artigo de revisão adota o protocolo PRISMA [1] para analisar a literatura existente sobre energia fotovoltaica em escala de utilidade pública, energia fotovoltaica distribuída, energia solar concentrada, desempenho em regiões desérticas, integração à rede e industrialização. A revisão da literatura existente indica que os planos nacionais da Arábia Saudita estão voltados para a implementação de energia fotovoltaica em escala de utilidade pública e energia solar concentrada, além do compromisso paralelo de aumentar a participação de energias renováveis na matriz energética nacional para cerca de metade até 2030 [2, 3]. A revisão da literatura existente indica que a implementação de projetos foi acelerada por licitações competitivas e parcerias público-privadas, com projetos emblemáticos como Sakaka e Sudair demonstrando o compromisso da Arábia Saudita em passar das metas à implementação [4, 16, 17]. A revisão da literatura existente indica que o desempenho da energia solar na Arábia Saudita é limitado por fatores específicos do deserto, como tempestades de poeira, escurecimento por aerossóis e temperatura dos módulos, bem como por fatores específicos do sistema de energia solar, como flexibilidade da rede, licenciamento, viabilidade financeira e

standardizing land and grid interfaces, industrializing O&M and land cleaning, integrating PV with storage and demand response, and localizing high-value PV value chain activities. A research roadmap could be suggested to enhance comparability, address gaps in existing literature on operational yields in different provinces, and support decision-making.

Keywords: Saudi Arabia. Solar Photovoltaic. Concentrated Solar Power. Vision 2030. Desert Soiling. Grid Integration. Localization.

prontidão da cadeia de suprimentos local [20, 23, 24, 25]. A revisão da literatura existente indica que os próximos passos na implementação da energia solar na Arábia Saudita estão menos focados em determinar a viabilidade da implementação da energia solar e mais em orquestrar uma escala confiável, padronizar as interfaces de terreno e rede, industrializar a operação e manutenção e a limpeza do solo, integrar a energia fotovoltaica com armazenamento e resposta à demanda e localizar atividades de alto valor agregado na cadeia de valor da energia fotovoltaica. Poderia ser sugerido um roteiro de pesquisa para melhorar a comparabilidade, abordar lacunas na literatura existente sobre rendimentos operacionais em diferentes províncias e apoiar a tomada de decisões.

Palavras-chave: *Arábia Saudita. Energia Solar Fotovoltaica. Energia Solar Concentrada. Visão 2030. Sujidade Desértica. Integração à Rede Elétrica. Localização*

1 INTRODUCTION

Saudi Arabia has a privileged position in terms of solar resources, considering that it is one of the top-ranking countries in the world in terms of solar intensity. Additionally, the curve representing the electricity supply peaks in the middle of the day. This makes it technically compatible with solar power generation. However, Vision 2030 has elevated the privileged position in terms of solar resources to a higher level by articulating it as a national transformation program that includes solar power and the future prospects of Saudi Arabia in terms of industrialization, employment generation, and export potential. Initial studies on the industrial localization of PV have indicated that the potential of Saudi Arabia in terms of localizing a significant part of the value chain is high. Additionally, there is a plan to achieve a renewable portfolio of 27.3 GW by 2023. Furthermore, there is a plan to have a PV-dominant mix by 2030, which has already been articulated [7]. From 2020 onward, there has been a widening of the policy narrative in terms of the potential of renewable energy in meeting the future energy demands. The Ministry of Energy now talks about having an optimal mix that is the 'most efficient and least costly,' which includes renewables and gas. However, it also mentions that renewables would constitute 50% of the mix by 2030 [3, 22]. At the same time, there has been a strengthening of the position of Saudi Arabia in terms of responding to climate change issues. Green finance frameworks and initiatives have already been put in place that articulate the goals of Saudi Arabia in terms of reducing greenhouse gases [5, 12]. The convergence of these policy narratives indicates that the expansion of solar power in Saudi Arabia is now being evaluated on the basis of repetition. From the point of view of logistics, the implementation of solar power on a massive scale is a ‘material movement’ problem, where the construction of a solar power plant on a massive scale requires the transportation of a substantial volume of materials, which include solar panels, steel, wires, transformers, and inverters, in the ports, industrial areas, and desert areas of Saudi Arabia. The solar power plant, when implemented on a massive scale to the tune of tens of gigawatts, is not just a problem in terms of the time it takes to construct the plant, but also in terms of supply chain issues, which include shipping, customs, warehousing, and equipment supply, which is particularly relevant in the case of transportation equipment, which has to be transported in high-temperature regions. The Vision 2030 program, which includes the industrialization initiative, has implications not just in terms of solar power as a policy intervention, but also in terms of facilitation, which is a part of logistics, which determines not just the arrival of the solar power plant at the site where it has to be constructed, but also its assembly and delivery [2, 7]. The Annual Report on the 2024 Vision 2030 is a broad overview of the status of execution. The installed base of renewable energy is growing, and the targets set in the 2030 Vision to deliver 50% in the electricity sector are reaffirmed [2]. While Annual Reports may not be a substitute for actual figures on the performance of the engineering sector, they do provide a broad overview, which is followed across the globe in understanding the execution capabilities. The key is delivery, not targets. In addition to that, the level of irradiance in Saudi Arabia is quite high. However, the development of solar energy in Saudi Arabia is not as simple as it might sound. For example, the solar plants have to be operated under the influence of dust storms, sand abrasions, temperature, and the variation in the amount of aerosol, which impacts the ratio of direct/diffuse irradiance [24]. The impact of soiling on solar plants is quite high in terms of the power lost. The decision on the cleaning of solar panels also has to be taken under consideration in terms of the scarcity of water [23, 26]. The aforementioned discussion on the development of solar energy in the kingdom is based on the concept of a socio-technical system. This is a concept that deals with the interaction of the quality of the resource base, technology, project delivery institutions, O&M practices, and grid integration.

2 AIM AND OBJECTIVES OF THE STUDY

AIM: To provide an evidence-based overview of the status quo of solar energy in Saudi Arabia (2020-2025), the challenges which impede the application of solar energy in Saudi Arabia in accordance with Vision 2030, and the strategic opportunities which can be seized in accordance with Vision 2030.

OBJECTIVES: To identify the current targets, policy instruments, and project strategies in solar energy in Saudi Arabia, identify the performance limitations in solar energy applications in Saudi Arabia, identify the integration instruments which can be applied in solar energy in Saudi Arabia, identify the localization limitations in solar energy in Saudi Arabia, and propose a research and practice route towards a viable objective which can be measured in accordance with Vision 2030.

3 METHODOLOGY

3.1 Review design

The current study has been undertaken by applying the structured literature review approach in accordance with the PRISMA 2020 reporting item checklist [1]. The literature review has been undertaken on the basis of a mixed evidence base, which includes peer-reviewed journals and other authoritative sources, which may also include government programs, official annual reports, and market reports.

3.2 Search strategy and eligibility

Literature was searched by using a combination of words like “Saudi Arabia” AND “solar PV,” “distributed photovoltaics,” “concentrated solar power,” “soiling,” “dust storms,” “grid integration,” “Vision 2030,” “localization.” The literature was limited to literature which was written between the years 2020-2025, literature which was written in English, and literature which was related to solar energy in Saudi Arabia. The literature which was written about other countries was excluded since it does not provide a general view of solar energy in desert environments.

3.3 Screening and synthesis

The data will be presented in a structured manner. The structure will have columns like ‘technology type,’ ‘geographic context,’ ‘performance type,’ ‘grid type,’ ‘enabling type,’ etc. The data will be presented in a narrative format. The data will also be presented if it is collected.

4 CURRENT STATUS OF SOLAR ENERGY IN SAUDI ARABIA (2020-2025)

4.1 Policy and targets

The common thread among sources published between 2020 and 2025 is the focus on solar PV in the Kingdom’s renewable energy policy. Reports published by Vision 2030 between 2020 and 2025 reaffirm the Kingdom’s commitment to its renewable energy sector, which is expected to contribute a substantial amount to its electricity mix in 2030. The Kingdom’s narrative on its renewable energy policy is unified in its assertion that it will contribute 50% to its electricity mix in 2030 [2-3]. Similarly, academic synopses published on the Kingdom’s energy policy assert that it aims to achieve a 58.7 GW capacity in its renewable energy sector by 2030, with solar PV being the largest contributor to its energy mix, followed by wind and CSP respectively [8-9]. The Kingdom’s narrative on its energy policy has shifted from targets to a more programmatic approach, as seen in its Ministry of Energy narrative on its renewable energy policy. The narrative in its energy policy is now more focused on its cost-minimizing approach and its intention to replace liquid fuels with renewable energy sources. The number of rounds in its procurement system has increased, as seen in its SPPC [3,14].

4.1.1 Program architecture and procurement

The architecture of the procurement process in Saudi Arabia is designed through SPPC processes that qualify bidders, provide tender documentation, and standardize offtake agreements under the National Renewable Energy Program. The release of the qualification of bidders in the public domain for large tender announcements is a critical point that indicates the engagement of the market and the extent of consortia that are capable of executing IPPs at scale [14]. The procurement process is critical in reducing prices; at the same time, it puts pressure on the execution capabilities of the developers; hence, the procurement process should be synchronized with the readiness of the grid, land surveys, and permitting to facilitate the timely delivery of the awarded projects.

4.2 Utility-scale PV build-out

The story of solar power projects in Saudi Arabia has been changing from the technical and financial viability of solar power projects towards commercial operation of utility solar power plants since 2020. Sakaka has been mentioned as the first utility-scale renewable energy project of the national program [4]. By 2023-2024, Sudair (1.5 GW) has created a new milestone in the build-out of solar power projects in Saudi Arabia, as it has reached commercial operation in phases, thus becoming a role model for the commercial operation of utility-scale PV projects in Saudi Arabia [16, 17]. A large amount of new capacity has also been declared at the financial closure and procurement stages, including the solar power projects at Al Shuaibah, which have an aggregate capacity of more than 2.6 GW, with high-profile national and private sector players [18, 19].

4.2.1 Al Shuaibah and pipeline acceleration

The financial close announcements of Al Shuaibah 1 and 2 projects with a cumulative capacity of over 2.6 GW indicate an increasing degree of cooperation between domestic anchor investors and experienced project developers. Furthermore, these announcements reaffirm that the Saudi Arabia pipeline consists of clusters of projects with multi-gigawatt capacities.

4.3 Distributed PV and behind-the-meter adoption

Distributed PV can be an important contributor to the capacity development process in Saudi Arabia as an alternative to other options of capacity additions. Recent studies on building-level distributed PV adoption in Saudi Arabia point to tariff structures and regulatory clarity, as well as PV-battery combinations, as critical factors to determine the viability of PV systems in Saudi Arabia [28].

4.3.1 Enabling rules for distributed PV

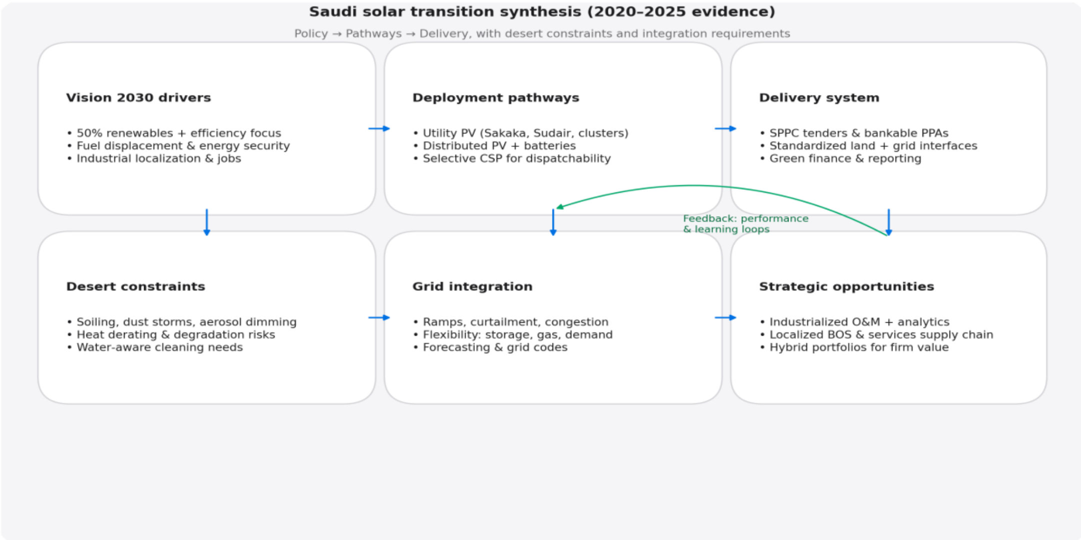
Distributed PV has a potential role to play in industrial decarbonization and providing security benefits to commercial and industrial sectors. However, to deploy distributed PV, there is a need to understand interconnection rules and tariff structures. Recent studies on building-level PV deployment in Saudi Arabia have shown that differences exist in the viability of PV based on various assumptions regarding electricity prices as well as technology choices and battery sizes. This shows that policy stability plays a role in PV development. From a system point of view, PV has a potential role to play as a flexibility resource with smart inverters and storage technologies.

4.4 CSP and dispatchable solar

CSP is part of national plans as a smaller component with strategic value because of the potential offered by thermal energy storage to provide dispatchability. From a techno-economic point of view, CSP has been shown to be important because of issues regarding cost trajectories, value of firm capacity, as well as value of ancillary services within a high-PV system [29]. The question that is being asked within the Saudi planning process is how much dispatchable solar is required to supplement low-cost PV?

Figure 1

Presents a conceptual synthesis of the Saudi solar transition as a multi-layered socio-technical system, linking Vision 2030 policy drivers with deployment pathways, delivery systems, environmental constraints, and strategic opportunities.



The framework illustrates that solar energy deployment in Saudi Arabia is not a linear progression from policy to implementation, but rather a feedback-driven system, where operational performance and environmental constraints continuously reshape planning, investment, and technology choices. This conceptualization provides a basis for understanding solar energy transitions in other arid regions, where environmental conditions play a central role in shaping system outcomes.

Table 1

Selected Saudi solar milestones and flagship projects referenced in 2020–2025 sources.

Project / program	Segment	Capacity	Key milestone (2020–2025)	Strategic relevance (Vision 2030)
Sakaka PV IPP (Al Jouf)	Utility PV	300 MW	Commercial operation (reported in national program materials, 2020–2021)	First utility-scale NREP project; template for IPP contracting and grid interconnection [4].
Sudair PV IPP (Sudair Industrial City)	Utility PV	1.5 GW	Phased commercial operation during 2023; full commercial operation reported in 2024	Scale benchmark; tests desert O&M, tracker reliability, and financing at gigawatt scale [16–17].

Project / program	Segment	Capacity	Key milestone (2020–2025)	Strategic relevance (Vision 2030)
Al Shuaibah PV 1 & 2 (Makkah Province)	Utility PV	>2.6 GW	Financial close announced in 2023; scheduled commissioning into 2025	Pipeline acceleration via large clusters; highlights transmission planning and logistics capacity [18–19].
SPPC / NREP Round 5	Procurement	~3.7 GW	Qualified bidders announced 2024	Signals market depth and competitive procurement; enables faster tender cycles [14].
Renewables & gas optimal mix	Policy	50/50 (2030)	Program framing reiterated 2021–2024	Positions solar within system efficiency and liquid-fuel displacement strategy [3,22].
Desert soiling evidence base	Operations	—	Saudi-focused reviews and experiments published 2022–2024	Soiling losses and aerosol variability require standardized metrics and cleaning industrialization [23–25].
Distributed PV + storage	Demand-side	—	Building-sector analyses published 2024–2025	Enables peak shaving and resilience; depends on interconnection rules and tariff design [28,30].

5 KEY CONSTRAINTS TO SCALING SOLAR IN ARID SYSTEMS: A SYSTEM LEVEL PERSPECTIVE

The scaling of solar energy in Saudi Arabia is becoming increasingly constrained, not in terms of resource availability or cost competitiveness, but in terms of a complex mix of environmental, technical, and institutional constraints.

5.1 Environmental constraints: soiling, aerosols, and spatial variability

One of the key performance-limiting constraints for solar systems in desert environments is soiling. Soiling rates vary significantly for different regions due to differences in humidity and wind patterns. Coastal regions are characterized by higher adhesion due to higher humidity levels. Soiling in other regions, however, is affected by episodic dust storms. One of the key limitations in soiling research is the lack of a standardized soiling measurement system. This makes performance benchmarking difficult, which in turn makes research and financing difficult. This calls for a standardized measurement and reporting system for soiling research.

5.2 Thermal effects and performance derating

High ambient temperatures increase the temperature of solar panels. This leads to performance derating during peak irradiance conditions. This creates a paradox for desert-based solar systems: Peak solar irradiance leads to maximum performance derating. This performance derating can be addressed by selecting appropriate technology and optimizing system designs. This can also be addressed by employing sophisticated ventilation systems for performance derating due to temperature effects.

5.3 Water constraints and the industrialization of cleaning

However, the trade-off between ensuring that the panels are clean and at the same time ensuring that water is saved is a major constraint in the operation of desert solar farms. The development of alternatives for cleaning is, therefore, a promising pathway, but it also brings about new challenges, particularly regarding abrasiveness, cost, and scale. This, in turn, indicates that the cleaning of solar panels is not necessarily a straightforward process, but it is a complex optimization problem that needs to be addressed at a system-wide level, taking into consideration environmental, cost, and performance issues.

5.4 Grid integration and system flexibility

As the proportion of solar power increases, it is also expected to increase in the overall power mix of Saudi Arabia. As such, it is also expected that new challenges would arise in Saudi Arabia, particularly regarding issues of generating more power in the middle of the day, generating power in the evening, and curtailment of power in the evening. As such, it is expected that flexibility would be required in the power system of Saudi Arabia, which would also require the development of storage, demand response, flexible gas, and Concentrated Solar Power coupled with storage. The question, however, is whether these technologies are available or not. Rather, it is a question of whether these technologies can be developed, which would require advancements in forecasting, dispatch, and grid codes.

5.5 Institutional and supply chain constraints

Another factor, which may have played a major role in the development of solar power in Saudi Arabia, is the institutional or supply chain factor, which may require non-technical issues in the development of solar power in Saudi Arabia. Even though it is expected that competitive mechanisms would lead to a fall in prices, it also brings about new challenges, particularly regarding issues of time and developer margins. However, this also creates an important challenge in the development of solar farms, as a trade-off is involved in the development of the industrial sector and the rate of development. This, in turn, indicates that the future of solar energy in Saudi Arabia is not merely a technological challenge, but also a coordination challenge, as a number of factors are involved, which are technical, institutional, and environmental in nature.

6 STRATEGIC OPPORTUNITIES UNDER VISION 2030

6.1 From megawatts to a repeatable delivery system

The best strategic opportunity is to move away from project-to-project delivery to a standardized system. The reports on Vision 2030 have different indicators on the progress of installed and connected capacities in renewable energy. This is a move towards project execution. The programmatics on different rounds of procurements under SPPC can align with presurveyed locations on renewable energy projects. This can also align with standardized grid connections and timelines on land and environmental clearances.

6.2 Localization in the industrial sector and the solar supply chain

Localization is not only about employment; it is also about strategic risk management in the supply chain. The supply chain in the renewable sector should not have long lead times in logistics. The report on localization in Saudi Arabia has an opportunity to supply balance of system equipment to be localized in Saudi Arabia and to grow further in localization. This would also involve growing in localization with policy and industry support [7]. The reports on industrial localization have an opportunity to supply to the solar PV sector in Saudi Arabia. This would be in the priority sector under the national plan on renewable energy in Saudi Arabia [10]. Localization in the industrial sector in Saudi Arabia can also take a more pragmatic approach. This would involve those components in which Saudi Arabia can compete in the supply chain in the world market. This would involve petrochemicals in encapsulants, metals in structures, power electronics in inverter technologies, and project logistics.

6.3 Desert resilient operations as a competitive advantage

Another alternative is to develop desert resilient operations as a performance strategy that Saudi Arabia can develop capabilities in to export to other markets. This would be done through standardization of soiling measurement techniques, cleaning schedules, and certification of low-water cleaning technologies. This would enable the market to reward innovations in these areas and would also protect off-takers from performance risks. This is similar to the earlier proposition for the development of performance guarantees that has been argued in the literature [23,26].

6.4 Hybridization: PV+storage, PV+demand response, and PV+dispatchable solar

The high PV system has the advantage of hybridization. This can ensure the availability of energy when it is valuable. The literature on DG systems based on PV discusses the importance of PV+Battery systems, especially in the context of buildings. This is in terms of tariff and reliability issues [28]. Storage and flexible demand response can help in minimizing curtailment at the system level. Similarly, at the system level, CSP can have the advantage of dispatchable solar if value signals allow [29, 30]. Hybridization can be defined in terms of fuels avoided, peaking capacities avoided, emissions intensity, and reliability. This is different from the cost-based definition of hybridization in terms of LCOE.

6.5 Green finance, reporting, and international positioning

The green finance frameworks developed by the Kingdom of Saudi Arabia can be seen to connect investment in renewable energy with strategies at the national level. This can help in expanding the investor base for clean infrastructure investments [12]. Similarly, the Saudi Green Initiative can also be seen to connect the development of capacities in renewable energy with emission reductions. This can help in enhancing reporting consistency. This is especially true in the case of governments and corporate issuers [5, 13]. This can help solar developers in enhancing their reporting. This is especially true in the case of overcoming the challenges faced by companies in linking up with global sustainable finance taxonomies in the context of emission reductions, water usage in cleaning solar panels, biodiversity, and local content.

7 DISCUSSION: SYNTHESIS AND IMPLICATIONS FOR 2030

The literature reviewed confirms the existence of these three conditions to ensure success. Firstly, there is the issue of operational realism. This is mainly concerned with the modeling of PV performance in desert environments. Secondly, there is the issue of system integration. This is mainly a concern for the future when PV performance is significant. Thirdly, there is the issue of industrial capability. This is mainly concerned with the workforce and supply chain demands to meet the project pipeline envisioned in the 2030 Vision. In addition to these conditions to ensure success, there is also the issue of logistics planning. This is mainly concerned with the synchronization of port services, inland services, and parts storage services. This is also a concern for the future. One of the challenges that was evident from the literature reviewed concerning 2020-2025 is the lack of open data on the performance of solar plants in the Kingdom. Most of the research conducted is based on experiments done on specific plants. This is also evident from the focus of policy targets and milestones in policy documents. This challenge can only be addressed by developing a data landscape in the Kingdom. This would also help in bridging the gap between declared capacity and performance in the market.

8 RESEARCH AGENDA

The research focus in the future should be on: (i) solar resource and soiling maps at the provincial level by integrating ground measurement with satellite aerosol products; (ii) long-term degradation and reliability with Saudi Arabia temperature and dust chemical conditions; (iii) comparison studies on cleaning methodologies with respect to water usage, abrasiveness, and cost; (iv) system modeling to co-optimize PV, wind power, storage, gas, CSP, and increasing demand, and heat wave conditions; (v) supply chain and localization to estimate value addition, supply chain segments, and human skill sets. In terms of research methodologies, it is recommended to estimate effects and ranges to enable future meta-analytical research.

9 CONCLUSION

It is recommended that Saudi Arabia has successfully transitioned from solar aspirationalism to actualism in 2020-2025 with the help of Vision 2030 programs. The limiting factors to scaling up solar in Saudi Arabia are no longer related to resources. The limiting factors to scaling up solar in Saudi Arabia are related to system and operation issues in the desert environment. The strategic opportunities to scaling up solar in Saudi Arabia are related to desert-resilient O&M methodologies, standardized project interfaces, hybrid solar-wind-PV with storage and demand response, and supply chain segments where Saudi Arabia has a competitive advantage. Therefore, if the enablers to scaling up solar in Saudi Arabia are effectively integrated, solar has the potential to be a key component in Saudi Arabia's future electricity mix.

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Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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