



## Utility-Scale Solar Photovoltaic Development in Saudi Arabia: Technical, Economic, and Policy Perspectives

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**Abstract:** The deployment of utility-scale solar photovoltaic (PV) systems in Saudi Arabia has been fast-tracked in the period 2020-2025 with the aim of diversifying the energy mix, cutting greenhouse gas emissions, and localizing the industrial sector in the Kingdom's Vision 2030 strategy. Although the solar resource potential is high in Saudi Arabia, the deployment of giga-scale solar PV systems in the Kingdom faces challenges in the desert environment and the procurement process and the rate of institutional learning. This review article seeks to provide a synthesis of evidence on the development of utility-scale solar PV systems in Saudi Arabia in the period 2020-2025 from three different angles: (i) the effectiveness of solar PV systems in the desert environment; (ii) the economics of solar PV systems in a competitive procurement process and the rate of institutional learning; and (iii) the policy and regulatory environment that provides a conducive environment for the development of solar PV systems in Saudi Arabia. As a guideline for the reporting of the review article, PRISMA 2020 was used as a template for the transparent reporting of the review article [1]. Here, we discuss the implementation of national-level targets in Saudi Arabia in terms of specific project-level mechanisms. This paper uses existing literature on PV in desert environments, such as the impacts of soiling in Saudi Arabia and mitigation strategies, techno-economic studies of utility-scale PV in different cities in Saudi Arabia, localization constraints/avenues, etc. This paper attempts to synthesize existing literature on PV in desert environments. This paper concludes that the competitiveness of utility-scale PV in Saudi Arabia is supported by irradiance conditions and a decline in global costs. This paper concludes that the key to sustainable implementation of utility-scale PV in Saudi Arabia lies in the integration of three "execution interfaces"—site interface, plant interface, and system interface. This paper provides an integrative framework and review-based roadmap to project developers/policymakers in Saudi Arabia in the context of utility-scale PV. This paper provides a set of recommendations to standardize data/resources, desert environment-based plant engineering, O&M, grid integration, procurement strategies, etc. This paper concludes with a set of research questions.

**Keywords:** Utility-Scale Solar PV, Saudi Arabia, Vision 2030, National Renewable Energy Program, REPDO, SPPC, PPA, Grid Code, Soiling, LCOE, Localisation.

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## 1. INTRODUCTION

Traditionally, Saudi Arabia's electricity system is based on oil and gas resources.

Nevertheless, the strategic direction in Saudi Arabia is to transition to a diversified and low-carbon-based electricity system while ensuring security. This is clearly emphasized in the annual reports of Vision

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2030 and the Saudi Green Initiative, focusing on renewable electricity as an important part of this transition, which includes an increase in the percentage of electricity generated from renewable energy by 2030 [2, 3]. At the implementation level, Saudi Arabia is achieving this transition to a diversified and low-carbon-based electricity system by a competitive process and large independent power producer projects. At the level of important organizations in this transition, there is the Ministry of Energy and the principal buyer for PPAs. Solar photovoltaic plays an important role in Saudi Arabia's transition to a diversified and low-carbon-based electricity system. This is due to the fact that solar photovoltaic technology is modular and easy to implement in comparison to other technologies. Nevertheless, the high speed of implementation of solar photovoltaic technology might cause complexity in this system. This is because solar photovoltaic is a long-term asset, and its performance is dependent on a variety of factors. Moreover, the role of solar photovoltaic in this system is great, which in turn might increase the level of forecasting and grid code compliance in this system. Regarding Saudi Arabia, the level of grid code compliance in this system is clearly defined in the Saudi Arabian Grid Code and interconnection procedures, which specify technical requirements for users of the transmission system [10]. The body of literature on solar deployment in Saudi Arabia has increased from 2020 to 2025, from discussions on "potential" to discussions on deliverability and bankability. Statistics from the nation's statistical data show that there are existing solar projects in the country, and the aggregate capacities of these projects are at multi-gigawatt levels as of 2024 [4]. Documentation and reports from the market show that the existing project pipeline includes multi-gigawatt solar projects such as Sudair and Al Shuaibah [6-9]. The question for scholars and researchers now is no longer on deliverability but rather on how to deliver in an efficient and effective manner and to extract maximum value from solar deployment in Saudi Arabia to achieve the purposes and objectives set out in Vision 2030.

This article makes a significant contribution to the existing body of knowledge and literature on the subject matter in the following ways: It brings multiple perspectives under one narrative, as expected in Q1 journals and publications. Discussions are also made on method and managerial relevance. Utility-scale solar deployment is not considered as an "engineering" choice but as part of a larger "socio-technical" program that requires coordination from multiple disciplines.

## **Aim and Objectives of the Study**

### **Aim of the Study**

The aim of the study is to synthesize existing evidence from the period between 2020 and 2025 to inform the development of utility-scale solar PV in Saudi Arabia and develop an integrative framework and methodology roadmap for technical performance, project economics, and policy design towards Vision 2030.

### **Objectives of the Study**

The objectives of the study are to assess the current status and project pipeline of Saudi Arabia's utility-scale solar PV from 2020 to 2025 based on official reporting and project documentation [2-9].

The second objective is to synthesize evidence to inform Saudi Arabia's utility-scale solar PV, including technical performance, such as resource assessment, site selection, module and tracker selection, thermal and soiling effects, and O&M strategies [12-20].

The third objective is to synthesize evidence to inform Saudi Arabia's utility-scale solar PV, including economics, such as cost, LCOE, and local content, and financing constraints and their effects on project economics and delivery in Saudi Arabia's utility-scale solar PV sector [11-16].

The fourth objective is to synthesize evidence to inform Saudi Arabia's utility-scale solar PV policy and regulatory mechanisms, including policy and regulatory frameworks, and their effects on project delivery in Saudi Arabia's utility-scale solar PV sector.

The fifth objective is to develop research gaps and review-informed roadmap for future research and practice in Saudi Arabia's utility-scale solar PV sector, with a focus on reproducibility, bankability, and system efficiency.

## **2. REVIEW METHODOLOGY**

### **2.1 Design and Reporting**

The paper is a systematic review, and a narrative synthesis methodology has been used. The methodology used in the paper is replicable, and all the guidelines mentioned in the "PRISMA 2020: a reporting guideline for systematic review and meta-analysis of health interventions and other interventions and their effects" [1], have been followed in the paper. A number of disciplines, like engineering and economics, have been included in the synthesis methodology used in the paper. Hence, a conceptual methodology has been used in the paper instead of a quantitative methodology used in a meta-analysis.





degradation and mitigation measures such as cleaning, which are applicable in Saudi Arabia. A general review of soiling effects and mitigation measures confirms that the effect of soiling is more pronounced in arid and semi-arid regions, and cleaning needs to be integrated into O&M economics rather than being an ad hoc solution to existing plants.

#### **4.4 O&M Strategy, Cleaning Technologies, and Digital Performance Monitoring**

O&M strategy is a key driver in ensuring that the performance is optimal and hence that the long-term yield and LCoE are achieved. In the case of Saudi Arabia, cleaning is a major aspect in the O&M strategy, and there are various constraints that affect the O&M economics in Saudi Arabia. A recent review on the robotic cleaning of PV systems in the desert and arid zones of the world has confirmed the move from manual cleaning to robotic cleaning of larger PV systems and has provided an overview of performance recovery and O&M feasibility in these regions, such as Saudi Arabia, with a focus on robotic cleaning solutions and larger assets and regions [20]. The use of digital monitoring of performance, such as SCADA, inverter monitoring, and performance monitoring, is a useful tool in identifying early warning signs of system degradation, such as soiling and tracker misalignment, and in providing a basis for benchmarking and learning, such as comparing and assessing energy yield from various portfolios of assets.

#### **4.5 Performance Modelling, Yield Uncertainty, and Bankable Assurances**

For utility-scale PV systems, the credibility of the financial model depends on the credibility of the yield model. The uncertainty in the yield for Saudi Arabia arises from the annual variations in irradiance, temperature, and soiling. The assumptions for the bankability of the financial models based on the data that is currently available are of great importance to investors and lenders. The resource data can help reduce the premiums for uncertainty by improving the irradiance data and making it easier to compare the sites. However, the resource data accuracy is not the only requirement for the utility-scale PV systems. The loss assumptions for the utility-scale PV systems, such as soiling loss, mismatch loss, clipping loss, and tracker loss, are key factors for the P50/P90 spreads. The soiling loss is a part of the utility-scale PV system that is quite different from the soiling loss in other locations. Studies from Saudi Arabia have identified soiling loss as a key factor for the utility-scale PV systems. A frequency and a rate need to be a part of the soiling loss models for the utility-scale PV systems. Soiling loss is a key factor for the utility-scale PV systems in other studies too. The key findings from the study

were that a system of systems approach for soiling loss needs to be implemented for the utility-scale PV systems. This includes factors such as dust properties, surface chemistry, humidity, cleaning, and operational constraints. The key findings from the study were that the loss due to soiling loss for the utility-scale PV systems is nonlinear.

#### **4.6 Technology Evolution for Desert Utility-Scale PV**

PV technology has undergone rapid development in terms of larger modules, increased power, trackers, and bifacial modules. In terms of Saudi Arabia, bifacial modules would be a good option since the reflectance would be high in desert conditions. However, bifacial technology has several factors associated with it, such as mounting height, row spacing, ground treatment, and rear surface soiling. Techno-economic studies on bifacial technology in arid regions have been conducted, which have highlighted increased energy yields compared to monofacial modules. Moreover, bifacial costs would be viable in specific conditions. In terms of Saudi Arabia, the key issue from a technology perspective would be to identify technology options such that even in stressed conditions, technology costs would be viable. Larger modules and increased DC/AC ratios would reduce the capex costs per watt but may increase thermal stresses and clipping losses. Similarly, trackers may increase energy yields but may also increase mechanical failures. Thus, best technology would not be a matter of yield but reliability. In terms of operations and logistics in Q1, the key performance metric would not be based on peak power but predictable power over a long term.

### **5. Economic Perspectives**

#### **5.1 LCOE Drivers and Techno-Economic Evidence for Saudi Cities**

The LCOE of large-scale, utility-scale, and solar power projects is influenced by capex requirements, opex requirements, and financing and energy yields. Although the irradiance would be beneficial, the impact of soiling and heat would be significant, but it is uncertain to what extent this would be mitigated. A techno-economic analysis, including comparative studies, would provide techno-economic evidence to support the economic case and competitiveness of solar power in the region. This would include studies conducted in 40 Saudi cities [12]. The economic competitiveness would also be influenced by the solar industry's global supply chain cycles, including prices of solar modules and shipping costs, impacting EPC costs, which would be significant in the case of large-scale solar power projects with multi-year project delivery cycles.

## 5.2 Procurement, PPAs, and Bankability

The majority of the solar power projects in Saudi Arabia have been procured and have PPAs. From the perspective of project bankability, the key considerations in PPAs include land and permitting, grid connection, curtailment, change in law, and indexation. In the case of projects like Sudair, the success of the project would emphasize the importance of financial closure as a determinant of project bankability. The long-tenor PPAs are also vital to the stability and low-cost debt finance, which is vital to keep tariffs low. However, high-competitive tendering also poses a high level of project risks, and there is also a possibility that project sponsors might under-invest in O&M, under-estimate the impact of soiling, and also under-estimate their own finance costs. Hence, it is vital to design the procurement model in a way that it incentivizes project sponsors to deliver on their plans and performance guarantees rather than focusing on tariffs.

## 5.3 System Value, Curtailment Risk, and Flexibility Economics

With higher levels of PV, the incremental value of higher levels of output from additional PV may fall as the levels of output from additional PV rise in the middle of the day during peak hours. This calls for additional flexibility in the system, which could be in the form of grid enhancement, DSM, inter-regional transfer, or storage. In all these options, even though storage may not be physically related to the above options, system value and curtailment risks have to be factored in to avoid the situation in which "cheap PV" turns out to be inefficiently utilised. This is also the point at which the system interface plays an economically critical role.

## 5.4 Financing Structure, Risk Allocation, and Cost of Capital

Cost of capital may be one of the most important factors contributing to LCOE in utility-scale PV. Even long-term PPAs may provide some risk mitigation against revenue risk, but costs of capital will always be a reflection of risks associated with construction risk, grid risk, and long-term variability. Empirical studies on investment in renewable energy projects in Saudi Arabia reveal the significance of investment being driven by risk perceptions rather than resource availability. Investment in renewable energy projects in Saudi Arabia was found to be a reflection of investment based on risk attribution to those best able to manage risk. There are three risk factors associated with Saudi Arabia's PV market. Construction risk includes supply chain risk, desert logistics risk, etc. Grid risk includes grid connection risk, etc. Performance risk includes soiling risk, degradation risk, etc. Cheaper tariffs are associated with all three risks being well managed. For example, grid connection risk can be well managed by

incorporating explicit grid connection milestones. Similarly, performance risk can be well managed by incorporating performance guarantees. Similarly, explicit O&M plans can reduce yield risk premiums. From a logistics perspective, project finance and project delivery are intertwined. Schedule delays can increase costs of capital during construction, which can increase liquidated damages. This can increase costs even if tariffs are low. One of the efficiency metrics associated with Saudi Arabia's PV programmes is time-to-COD reliability.

## 6. Policy and Regulatory Perspectives

### 6.1 Targets, Institutions, and Programme Governance

The policy direction in Saudi Arabia is influenced by the need to report against the Vision 2030 targets and emission reduction targets set out in the Saudi Green Initiative [2, 3]. Programme governance in Saudi Arabia is facilitated by the tender pipeline, contracting standards, and the tender pipeline buyer. It is vital to have clarity in this area, especially with regard to utility-scale PV, where there is a high lifecycle and a high number of interfaces.

### 6.2 Procurement Design and Market Signalling

Competitive tendering is a vital aspect of the drive to reduce costs and must be designed to secure performance in the long term. Good procurement design in Saudi Arabia is characterized by a clear qualification and tender evaluation process. Good procurement design in Saudi Arabia is further characterized by a learning and adaptive tender design, where there is an ability to change the tender data in response to learning from actual operational experience, e.g., soiling losses, degradation, etc.

### 6.3 Grid Code, Interconnection, and System Planning

The Saudi Arabian grid code is a set of technical rules governing the operation of PV plants to secure the safe operation of the plants and stability of the electrical system, including the obligations of users with regard to the transmission system [10]. The need to comply with the grid code is a vital aspect in Saudi Arabia, which influences the design and costs of the system. The system's planning process must take into account the location of the PV system and the extension of the grid to accommodate additional capacity.

### 6.4 Data Transparency and Resource/Project Information as a Public Infrastructure

Good quality resource/project information can serve to minimize risk premiums and enhance the efficiency of the bidding process. Disclosure of resource capacities, operating status of projects, project pipelines, etc., will serve to build confidence

in the market, which will be beneficial for research activities. National statistics on the operating status of renewable projects/capacities will form an essential part of a building block in an environment of transparency.

### 6.5 Regulation, Data Governance, and System Integration as a Scale for Capacity

As the capacities of PV systems increase, the need to shift from the present system of regulating each and every project will be felt more and more. Grid Code will form an essential part of providing a basis for safe and efficient operation of the inverter, ride through capability, etc. Utility-scale PV systems require tools such as regional hosting capacity calculation, transmission system planning, curtailment management, etc. An international review of integration of renewables into the electrical systems of the Gulf Countries states: "Renewable energy deployment has been rapid in the GCC. Achieving targets set in national plans will require continued policy attention to system integration and market design." Data governance could potentially have a significant impact in helping to facilitate system integration. For example, data from existing projects could provide beneficial information to help improve forecasting, etc., and create a more data-driven approach to bettering procurement assumptions, etc. National statistics are available, but system optimization requires more precise data, such as hourly generation profiles, curtailments, etc. A more data-driven approach to data could mean utilizing data from plants as a learning tool,

anonymized if necessary, to better improve interconnection, tender template improvement, etc.

### 7. Integrative Framework and Strategic Opportunities under Vision 2030

The evidence shows that the success of utility-scale PV in Saudi Arabia is not based on any of the above factors individually, but on the successful coordination of all three interfaces of execution.

**Interface 1:** Site interface. Land and resources data normalisation reduces development risks and time to market. Resource information platforms and permitting processes can act as public infrastructure.

**Interface 2:** Plant interface. Desert robust engineering and soiling/O&M strategy guarantee a lifetime yield. Monitoring and maintenance discipline reduce performance drift and offer a learning opportunity.

**Interface 3:** System interface. Grid integration and compliance with grid code requirements reduce curtailment risks and increase the economic value of PV. As the share of PV in the energy mix increases, flexibility is a key driver for economic optimisation. New opportunities for strategy emerge where intersections occur between: (i) co-optimisation of PV with water constraints and robotic cleaning technologies [20], (ii) the interface between localisation policy and quality and reliability specifications for scaling local industries with performance discipline [11-16], and (iii) the interface between operating data and design of procurement strategies for optimisation of bankability and risk premiums.

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**Table 1: Representative utility-scale PV projects and delivery implications in Saudi Arabia during 2020–2025 (selected examples)**

Project / indicator	Capacity (MW)	2020–2025 delivery insight	Key source(s)
Sakaka Solar Power Plant	300	Early utility-scale PV milestone; learning base for desert O&M and contracting	[5]
Sudair Solar PV	1500	Giga-scale financing and bankability signal; supports procurement learning and supply chain scaling	[6]
Al Shuaibah 1 & 2 Solar PV	2631	Large multi-project complex; highlights portfolio delivery and grid interface coordination	[7],[9]
Ar Rass Solar PV IPP	700	PPA-backed IPP; illustrates tendered PV scale-up and commissioning pathway	[23, 24]
Saad 1 Solar PV	300	Category project supporting regional diversification of sites; demonstrates construction-to-COD execution	[8-22]
Operating solar projects (national total, 2024)	3751	Aggregate operational capacity used for policy learning and statistics-led transparency	[4]

## 8. Research Gaps and Future Directions

Firstly, there is a need for more longitudinal data in the utility-scale solar PV research in Saudi Arabia, relating to the design choices such as module types, trackers, and cleaning strategies and the degradation and performance results. Secondly, quantification is needed in the system integration research, particularly in the evaluation of the risks related to curtailment, the need for ancillary services, and the economics of flexibility options in high solar penetration scenarios, with the context and grid code requirements in Saudi Arabia. Thirdly, there is a need to move beyond the descriptive approaches in the localisation research and focus on the evaluation of the effectiveness of different policy instruments in enhancing local capture without increasing system costs. To do so effectively, there is a need to improve the methodologies in the field. To do so effectively, there is a need to standardize the performance metrics such as PR, SY, and soiling rates. Further, it is important to clarify the underlying assumptions. To evaluate the policies effectively, it is important to leverage the change in procurement rounds and policies as a quasi-experiment to draw more credible inferences on what works to speed up and de-cost projects. Finally, it is important to integrate the logistics and supply chain elements into the research. Galgalopolis' research in the US and China is a useful reference point in this regard.

## 9. CONCLUSION

The development of utility-scale solar PV in Saudi Arabia from 2020 to 2025, from initial flagship programmes to a growth trajectory to support Vision 2030 and the Saudi Green Initiative, will be reviewed in this paper to illustrate that, whilst the solar resource in Saudi Arabia represents an opportunity, it in no way represents a guarantee of successful delivery of sustainable and cost-effective solar PV, which relies on the successful delivery of interfaces between site, plant, and system, with governance and institutional learning to inform delivery. From a technical perspective, evidence from this review

confirms that, in order to successfully deliver solar PV in Saudi Arabia, consideration of the unique conditions of a desert environment, such as soiling and cleaning economics, and designing solutions which need to be successful in a hot and dusty environment, is required. From an economic perspective, evidence from this review confirms that, in order to successfully deliver solar PV in Saudi Arabia, consideration of the fact that, whilst capital expenditure costs are a key driver of tender results, other factors such as bankable tender design, operation and maintenance costs, and system value need to be considered in a changing landscape of high PV penetration. From a policy perspective, evidence from this review confirms that, in order to successfully deliver solar PV in Saudi Arabia, consideration of the fact that, whilst tender and programme design are a key driver of successful delivery, other factors such as grid flexibility and data transparency need to be considered in a changing landscape of high PV penetration.

From this review, a clear strategic direction is evident, and it is proposed that in order to drive utility-scale solar PV in Saudi Arabia, a successful and sustainable part of a changing landscape in Saudi Arabian power, a programme approach to delivery, rather than a series of individual projects, is required to standardise data and permitting, engineer solutions to desert climate, and design tender and programme elements to balance bankability and local value creation.

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