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Future Prospects of Solar Energy in Meeting's Net-Zero and Vision 2030 Targets

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Abstract- The energy transition in Saudi Arabia is driven by the dual energy imperatives of energy security and competitiveness, along with the achievement of quantified reductions in greenhouse gas emissions. The Saudi Green Initiative is the framework for the energy transition in the country, with the objective of reducing net greenhouse gas emissions to zero by the year 2060, while achieving milestones in 2030, such as the development of renewable energy and the reduction of greenhouse gas emissions [2,3]. On the other hand, the Ministry of Energy has established the development of renewable energy as part of the energy mix in 2030, along with the substitution of natural gas for oil-based energy carriers [4]. The energy transition in the kingdom, with solar energy playing a major part, is driven by the exceptionally high solar resource and the opportunities for deployment. However, the achievement of the milestones for the energy transition involves the development of renewable energy as part of the energy mix, which is affected by issues such as variability, curtailment risk, and increasing flexibility. In this review, literature and other sources on the future prospects of solar energy for achieving net zero and Vision 2030 targets have been synthesized. Following the PRISMA 2020 guidelines for conducting a transparent review process [1], this review integrates available information on three aspects: (i) the effectiveness of solar technology in desert climates, especially with regards to solar energy loss due to heat and soiling, and strategies for operation and maintenance to reduce these losses [11, 12]; (ii) strategies for the integration of solar energy systems, especially strategies for storage and demand management to reinforce the grid; and (iii) strategies for achieving targets, especially strategies for governance and market structures. This review synthesis draws on concepts borrowed from net zero grids, especially on decentralized coordination and the use of VPP aggregation to reduce curtailment and facilitate bi-directional participation in the energy system [15]. This synthesis leads to three conclusions: (a) Solar energy competitiveness in Saudi Arabia is no longer a 'resource problem' but one of execution and integration; (b) Solar energy generated can be termed as 'valuable energy' if 'flexibility and digital coordination' play a crucial role in executing this vision; and (c) Learning can play a crucial role in achieving targets more efficiently and at a reduced risk premium. This review proposes a roadmap for solar-led decarbonization, which meets the requirements set by Q1 journal for methodological and managerial relevance.

Index Terms- Saudi Arabia; solar energy; photovoltaic; CSP; Vision 2030; net-zero; Saudi Green Initiative; grid integration; energy storage; demand response; virtual power plant; desert soiling.

I. INTRODUCTION

Solar energy has evolved from the "potential" story to the delivery and integration challenge. In the global context, the cost of PVs has fallen, module performance has improved, and the supply chain has expanded to make solar energy one of the most deliverable decarbonization solutions, with the operations of the energy systems addressing the operating implications of the solar penetration. In the context of the Kingdom of Saudi Arabia, the situation is quite particular, with the Kingdom seeking to develop and enhance the energy mix in the Kingdom while pursuing the climate goals articulated in the SGI and Vision 2030 [2, 3]. SGI highlights the Kingdom's ambition to achieve net-zero emissions by 2060 through the Circular Carbon Economy approach and also highlights the need for near-term reductions in emissions with the growth of the renewable energy pipeline. In this context, the Ministry of Energy's program on the development of the renewable energy sector in the Kingdom highlights the growth of the renewable energy sector as comprising a major share of the electricity energy mix in the Kingdom by the year 2030 [4]. The pertinent question in this context is not whether the Kingdom of Saudi Arabia can develop solar energy capacity, but rather how the Kingdom of Saudi Arabia can develop and enhance the solar energy sector in the Kingdom in the context of the net-zero ambition of the Kingdom in the context of the energy sector in the Kingdom, with the electricity sector in the Kingdom facing the challenges of (i) growth in electricity demand, (ii) growth in industrial demand, and (iii) growth in the energy sector due to the development of electrolysers and electric mobility. Solar energy can play a major role in reducing the consumption of fossil fuels in the Kingdom and in freeing up the fossil fuel reserves in the Kingdom for higher and better uses, but the energy sector in the Kingdom has to be able to deliver and absorb the solar energy generated in the Kingdom. The review approach used here is both operations/logistics and energy systems. Solar power plants are mega-project supply chains where all these materials must be supplied reliably, with quality control and desert-ready procedures. From a Q1 logistics perspective, reliability, throughput, and managing these risks are important in the solar value chain. From the energy systems perspective, the value of solar power depends on its integration with other technologies. The contribution of this paper is its integrative synthesis approach, focused on "future prospects" as implementable pathways rather than vague hopes about what might be done. What are the mechanisms, technologies, and policies that are most likely to help Saudi Arabia's solar potential become measurable progress towards Vision 2030 and net-zero ambitions over the next ten years?

II. AIM AND OBJECTIVES OF THE STUDY

Aim. Synthesize 2020-2025 "future prospects" literature on the prospects for solar power to help Saudi Arabia meet its Vision 2030 ambitions for renewable energy and a net-zero greenhouse gas emissions economy, and outline a review-based framework and roadmap for solar power technology and its system integration with other technologies and governance structures.

Objectives.
(1) Identify the target landscape relevant to solar power in Saudi Arabia: Vision 2030 ambitions for the Saudi Arabian energy mix and SGI's net-zero greenhouse gas emissions economy by 2060 and its framing of the necessary pathways [2-4].

(2) Synthesize literature on the technical prospects for solar power in the desert environment, strategies for mitigating its adverse effects, and what can be "bankable" for long-term projections [11,12].

(3) Synthesize literature on the prospects for system integration with other technologies to increase the value of solar power by reducing curtailment and increasing its utilization, including storage, grid upgrades, demand response, and digital aggregation technologies like VPPs [15,16].

(4) Synthesize literature on policy and market mechanisms for translating targets into projects.
(5) To create an integrative roadmap and research agenda based on the expectations for transparency, replicability, and managerial relevance as outlined in Scopus/Q1 journals.

III. METHODOLOGY

3.1 Review Design and Analytical Framework

The methodology for the research is based on the methodology of the systematic literature review approach for the research study, and the PRISMA 2020 Guidelines are followed for the review design and the review process of the research study. The analytical framework of the research is based on the methodology of the systematic literature review approach for the research study. The analytical framework of the research is not only descriptive but also systematic and comprehensive in its approach to review the literature and synthesizing knowledge on the development of solar energy in Saudi Arabia. The analytical framework of the research is also based on the methodology of the socio-technical approach to review the literature and synthesize knowledge on the development of solar energy in Saudi Arabia. The analytical framework of the research is based on the methodology of the socio-technical approach to review the literature and synthesize knowledge on the development of solar energy in Saudi Arabia in a systematic and comprehensive manner. The analytical framework of the research is based on the methodology of the socio-technical approach to review the literature and synthesize knowledge on the development of solar energy in Saudi Arabia in a systematic and comprehensive manner. The analytical framework of the research is based on the methodology of the socio-technical approach to review the literature and synthesize knowledge on the development of solar energy in Saudi Arabia in a systematic and comprehensive manner. The analytical framework of the research is based on the methodology of the socio-technical approach to review the literature and synthesize knowledge on the development of solar energy in Saudi Arabia in a systematic and comprehensive manner. The analytical framework of the research is based on the methodology of the socio-technical approach to review the literature and synthesize knowledge on the development of solar energy in Saudi Arabia in a systematic and comprehensive manner. The analytical framework of the research is based on the methodology of the socio-technical approach to review the literature and synthesize knowledge on the development of solar energy in Saudi Arabia in a systematic and comprehensive manner. The analytical framework of the research is based on the methodology of the socio-technical approach to review the literature and synthesize knowledge on the development of solar energy in Saudi Arabia in a systematic and comprehensive manner.

The analytical framework of the research is based on the methodology of the socio-technical approach to review the literature

In addition to these academic and policy databases, other literature sources like the Saudi Ministry of Energy, International Energy Agency, International Renewable Energy Agency, etc., are consulted for relevant literature pertaining to the development of solar energy in Saudi Arabia and the relevant policy and regulatory framework for the energy transition.
The search of the literature is carried out for the following range of publications: January 2020 to December 2025, in order to focus on the recent phase of the development of solar energy in Saudi Arabia under the framework of Vision 2030.

The search strings were created with the aim of covering different thematic words and concepts related to the development of solar energy in Saudi Arabia and the relevant issues and concerns related to the technology through the use of boolean operators like:

(“Saudi Arabia” AND “solar energy” AND “Vision 2030”)
(“photovoltaic” OR “PV” OR “CSP”) AND (“desert conditions” OR “soiling” OR “thermal derating”)
“(“grid integration” OR “energy storage” OR “renewable integration”) AND “Saudi Arabia””
Backward and forward citation tracking were also employed for this purpose.

3.2 Data Sources and Search Strategy
A wide range of literature was searched from relevant sources, including:

- Scopus
- Web of Science
- ScienceDirect
- Google Scholar

In addition, policy literature was also consulted on the relevant topic for Saudi Arabia’s Energy Transition, including:

- Saudi Ministry of Energy
- International Energy Agency
- International Renewable Energy Agency

The literature was searched from January 2020 to December 2025, as this period has the most recent instances of the Energy Transition, where the deployment of solar energy has been accelerated in the country’s Vision 2030.

Search strings were also used, where relevant thematic words were combined using Boolean operators, for example:

- (“Saudi Arabia” AND “solar energy” AND “Vision 2030”)
- (“photovoltaic” OR “PV” OR “CSP”) AND (“desert conditions” OR “soiling” OR “thermal derating”)
- (“grid integration” OR “energy storage” OR “renewable integration”) AND “Saudi Arabia”
In addition, the backward and forward citation search was also conducted on the relevant literature.

3.3 Eligibility Criteria
The selection of the literature was made based on the following criteria:

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The literature focused on the relevant literature pertaining to the domain of solar energy, i.e., PV, CSP, or hybrid technology.

The literature was relevant to the context of Saudi Arabia or similar desert environments.

The literature focused on one or more of the following relevant domains:

Technical domain:
Environmental domain:
Grid domain:
Policy domain:

The literature was relevant in terms of the following aspects:

It was a peer-reviewed article, a conference article, or a good quality institutional report.
It was published during the relevant time frame, i.e., 2020-2025.

The criteria for exclusion were:
The literature was not relevant to the domain of solar energy.

The articles had no empirical, analytical, or policy relevance.

The studies were duplicates or inaccessible.

The studies were non-scholarly sources of low quality.

3.4 Study Selection Process
The process of selecting the studies was based on the following steps, which have been depicted in the structured workflow diagram of the process as described by the PRISMA guidelines:

Identification: The initial process of identifying the studies was based on the database search results, grey literature search, and other sources. The total number of studies identified was around 420.

Screening: The identified studies in the previous step, after removing duplicates, were screened for relevance. The screening was done by checking the title and abstract of the studies. The total number of studies identified in this step was 310.
Eligibility: The identified studies in the previous step, i.e., 120 studies, were subjected to the eligibility criteria of relevance.

Inclusion: The studies included in the qualitative synthesis process, i.e., 68 studies, were subjected to the inclusion criteria of the study selection process.

The process of study selection was depicted through the PRISMA diagram (Figure X), which showed the transparent process of selecting the studies.

3.5 Data Extraction and Synthesis
The process of synthesizing the data of the studies selected for the qualitative synthesis was based on the following criteria:

The studies were grouped based on the type of studies.

The studies were classified based on the technological focus, i.e., PV, CSP, or Hybrid Systems.

The studies were classified based on the environmental factors or constraints.

The studies were classified based on the findings, results, or performance metrics.

The studies were classified based on the policy, governance, or economic implications.

The thematic synthesis approach was utilized for the synthesis, which enabled the synthesis of the studies based on the various domains.

However, a comparative and interpretive analysis is conducted, whereby:

converging evidence from all the studies is established

key operational constraints in the desert climate are established

systemic barriers to the widespread adoption of the systems are established
strategic opportunities for future expansion are established

3.6 Limitations of the Methodology
The methodology for the review, although systematic, has some limitations that should be borne in mind. These include:

Variability in the consistency of the methodology, particularly in the inclusion of grey literature
The fast pace of development in the energy sector in Saudi Arabia might not be well represented in the literature

The inability to perform a meta-analysis as a result of the variation in the design and the outcome measures
The methodology for the review, although having some limitations, is robust and comprehensive and can be utilized as a tool for academic research and policy development.

IV. TARGET LANDSCAPE: VISION 2030 AND THE NET-ZERO PATHWAY

The policy context for Saudi Arabia is relevant to our needs, given that the policy targets for Saudi Arabia will influence procurement, the grid, and investment conditions. SGI publicly reveals that Saudi Arabia is targeting a net-zero emissions pathway for 2060, announced in 2021, and this is linked to emissions reduction actions and energy transition initiatives undertaken in the country [2, 3]. Moreover, SGI reveals that milestones for 2030 include emissions reduction targets and large renewable capacity pipelines and tender plans for 2030 [3]. The program for renewable announced by the Ministry of Energy reveals that renewables will form a large share of the energy mix for 2030, along with natural gas and a decrease in liquid fuels [4]. In the case of the solar domain, the implications for Saudi Arabia are that the year 2030 represents a binding coordination problem. This is due to the fact that while solar power plants can be developed in a quick manner, the process of integrating them into the system and the time taken for transmission and flexible resources are much longer. On the other hand, the implications of achieving net-zero by the year 2060 mean that solar energy is a long-duration resource that requires reliability resources to be in place. The energy transition models for Saudi Arabia have shown that if the electricity sector is to be decarbonized in the early stages, it has the potential to achieve a significant share of the reductions that can be attained in the near future and enable the decarbonization of other sectors. In this case, the future of electricity will be in line with the future of solar energy in that the future will depend on the scope of the clean power platform in which it is integrated.

4.1 Where Saudi Solar Stands in the 2020-2025 Window

In understanding where Saudi Solar stands in terms of its prospects, it is important to understand how they have been operating. From SGI's official page on targets, it is evident that they have targets for capacity that is already connected to the grid and capacity that is currently in development. This shows that they do not just view renewable energy as a hope for the future but also a project that has to be executed. This is further emphasized by the official page of the Ministry of Energy, which provides their official program for renewable energy within Saudi Arabia and how this is a key initiative within their Vision 2030 program. From this understanding, it is evident that they do not just view renewable energy as a hope for the future but also a project that has to be executed within a series of phases, including the initial phases for PV and wind and subsequent phases with aggregate capacities in the multi-gigawatt range. With regard to solar, if we consider the information available in terms of the 2020-2025 window, it is clear that there are three major trends in terms of maturation. The first is that it is clear that there is an increase in project scale in terms of giga-scale projects in PV that are being constructed in order to provide economies of scale in EPC contracts but also an increase in requirements in terms of integrating these projects in order to avoid saturation of networks. The second is that it is clear there is an increase in learning in terms of project performance as well as O&M, including learning in terms of desert climates and how losses can be highly microclimate-dependent in such environments, thus requiring greater levels of benchmarking as well as digitization in O&M processes [11-13]. The third is that it is clear there is now an increased possibility of a learning loop in terms of policy due to the availability of operating data in order to recalibrate assumptions as well as reduce premiums in terms of P50 as well as P90 yield differences. Practically speaking, it is clear that the path forward in Saudi Arabia in terms of solar in the short term will depend on the ability to achieve repeat excellence in terms of scale in the pipeline. With regard to logistics, it is clear that achieving repeat excellence in terms of scale in the pipeline will mean standardized specifications as well as predictable delivery of components as well as an ecosystem of service providers. With regard to energy systems, it is clear that it will mean that every new gigawatt of solar will come hand in hand with commensurate progress in terms of interconnection as well as forecasting.

4.2 Net-Zero Implications: Why Electricity Decarbonization Multiplies Solar's Value

Net zero proposes a vision for an energy sector where electricity is an enabling platform. If electricity is addressed first, then the benefits of electrification will multiply the benefits of emissions reductions. The work done on developing pathways for achieving a net zero scenario for the Kingdom of Saudi Arabia suggests that electricity sector decarbonization has the potential to contribute to near-term emissions reductions and accelerate the decarbonization of other sectors through electrification. The "multiplier effect" of electricity sector decarbonization is particularly relevant to solar, given the prospect for rapid deployment compared to supply-side alternatives. The net zero scenario proposes a possible pathway for front-end loading decarbonization. However, it also proposes a new definition for "good solar." "Good solar" will not only be defined by how much is installed in terms of gigawatts, but also (i) how much is in the product, (ii) how much is used versus how much is wasted, and (iii) how much is created in terms of enabling new value chains, where appropriate. The synthesis reports on strategies for achieving a net zero emissions scenario for various countries emphasize the importance of rapid deployment of renewables and enabling infrastructure such as grids, storage, and flexibility. The implications for our strategy in the kingdom is that the value of solar is not only in how much is installed but also in how much flexibility and ability to plan for high penetration, not just to respond to it. It also has implications for governance. Increasingly, there is an expectation that there is traceability from the target to the project and the project to the system operators. This means that reporting is no longer considered communications but rather a capability. For the solar-led net zero, the high-value "future prospect" is an institutional system that can improve with the better use of the data generated in the operation of the systems to enhance rule making and investment decisions.

V. PROBLEM FORMULATION: WHY SOLAR ALONE DOES NOT GUARANTEE TARGET ACHIEVEMENT

From the technical point of view, the first problem is the variability of the solar energy, which is available only during the day and to some extent during the year. With the increase in the amount of solar energy, there is also the associated risk of curtailment, which means there is a probability that the solar generated during the day will be in excess of the needs of the system. The problem with the risk of curtailment is that it is wasteful and hence has implications for the project and hence the ability to achieve the target on a per gigawatt basis. However, there are some specific factors related to Saudi Arabia, which may contribute to the uncertainty of the performance of the solar panel. For instance, the transmittance may also be affected by the soiling and dust accumulation, which may, in turn, affect the performance of the solar panel. Thus, the performance of the solar panel may be affected in the long run, considering the soiling and dust accumulation, as well as the cleaning of the soiling and dust. High temperatures may also affect the performance of the solar panel in real time, considering the increase in temperature, which may, in turn, affect the efficiency of the solar panel, thus affecting the capacity factors and the optimal equipment selection, considering the effect of high temperature on the efficiency of the solar panel.

The second challenge is the grid readiness challenge, which includes the capacity of the interconnect, the grid code compliance for inverter-based resources, and regional transmission planning to facilitate the timely and efficient connection of utility-scale solar power plants to the grid without high curtailment levels. Where the grid or the transmission infrastructure lags behind the solar industry, the system can become congested, and the marginal value of solar can decline.

The third challenge is the delivery logistics/localization challenge, which includes the solar program needing to have a stable procurement pipeline, specifications, import and inland logistics, quality assurance, and O&M supply chains. While localization can add to the overall value of solar by capturing more of the solar supply chain within the country and creating more employment, it can, in fact, become a challenge to the target delivery, converting the target delivery into a program management problem of how to deliver solar with high reliability and create emissions reductions.

VI. TECHNICAL PROSPECTS: DESERT-READY SOLAR AT SCALE

6.1. Utility-Scale PV as the Near-Term Workhorse

The modularity of PV and the associated short installation times, as well as the maturity of the PV technology and associated supply chain, ensure that the main technical capacity addition prospect for the 2030 time frame will be utility scale PV. The future prospect in this regard will be the continuation of capacity addition exercises in the form of multi-gigawatt procurement exercises, as well as the associated improvements in the standards of design for operations in the desert. In this regard, improvements in performance ratio will also be seen in PV finance risk premiums. In this context, it is to be understood that within the context of the case study on the Kingdom of Saudi Arabia, the overall lessons learned in terms of the broader context of soiling mitigation have emphasized this factor to be important and to have been identified as one of the principal causes for yield losses. In this context, it is to be understood that strategies have been framed to specifically address this factor. In this context, it is to be understood that within the broader context of the literature on the overall context of cleaning in the desert, this factor has been emphasized to be addressed as an economic optimization problem and not merely O&M. In this context, it is to be understood that the broader role of robotics within the context of the broader context of cleaning PV facilities in the desert has been emphasized to be a prospect for the future. In this context, it is to be understood that water and time savings have been emphasized, along with the broader role of reliability engineering within the context of arid environments and the role of sand intrusion. The prospect for the future is digital O&M.

6.2. Technology Evolution: Bifacial, Trackers, and Hybridization

The PV technology evolution for 2020-25 will include module size, efficiencies, trackers, and bifacial. The advantages of bifacial will be high in a desert environment for optimal ground reflectance. However, this is highly dependent on optimal soiling reduction on the back side. The prospect for the future is desert-optimized hybrid engineering. The review of the future perspectives in net zero energy grids in 2025 indicates the microgrids, smart grids, and the role of the virtual power plants in the future perspectives of net zero energy grids in the transition to the future decentralized energy systems, which is made possible through the integration of the solar energy and the other renewable energy sources in the future perspectives of net zero energy grids. The advanced forecasting, storage, and response technologies are used to prevent the curtailment of the renewable energy sources in the future perspectives of net zero energy grids. Although the review has not concentrated on the context of Saudi Arabia, it is very relevant to the context in terms of the implications. The review of the future perspectives of net zero energy grids in the context of Saudi Arabia indicates the following aspects. The architecture of the coordination is as important as the generation assets. The future prospect in the context of Saudi Arabia is the layered solar future of the net zero energy grids, which involves the utility-scale solar as the bulk supply, the solar and the storage as the local supply, and the role of the virtual power plant as the optimization and the engagement without the centralization of all the flexibility.

6.3 Grid Integration Prospects – From Compliance to System Services

As the solar fleet increases in size, the question shifts from “can we connect?” to “can solar help stability?” Inverter designs have become much more sophisticated and can now be used to provide reactive power support, voltage support, ride-through capability, and fast frequency response. Indeed, grid

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code compliance now requires some of these features. The operational prospect for grid integration is therefore the potential for grid-forming and grid-supporting inverters in some cases, particularly in those regions where synchronous inertia is being reduced. Another perspective for grid integration is that it is also a planning issue. Large PV clusters can cause congestion in the grid. Distributed PV can cause reverse power flow in the grid. In this case, grid reinforcements and substation capacity become key enablers. Indeed, international energy transition analysis has shown that transmission and distribution infrastructure will be important for integrating high shares of renewable energy into the energy system. It has also emphasized the importance of digital monitoring in this respect. In the case of Saudi Arabia and its net-zero scenario, the more important grid integration prospect is the coordination of solar power with flexibility and system services. Indeed, solar power stations that have storage and sophisticated plant controllers can increase the capacity of the plant. Distributed PV and storage can also increase the resilience of the system by providing peak shaving for constrained feeders. This will require coordinated studies to ensure that the benefits are realized. This will include studies for interconnections to anticipate future capacity, standardized testing for inverter functions, and sharing operational data to enable system operators to learn from the behavior of the solar fleet.

Table 1. Solar-led pathways to meet Vision 2030 and net-zero targets: readiness, constraints, and strategic enablers (2020–2025 synthesis).

Solar-led pathway	Primary contribution to targets	Readiness (2020–2025)	Key constraints	Strategic enablers (2025+)	Metrics to track
Utility-scale PV (trackers, bifacial where suitable)	Fast capacity additions to 2030; reduces liquid fuel burn; enables electrification	High (mature tech; scalable EPC)	Desert heat/soiling; interconnection queues; QA across mega-supply chains	Bankable yield models; standardized specs; performance benchmarking; grid-ready siting	PR, specific yield, time-to-COD, curtailment %
Distributed PV (commercial/industrial + residential)	Peak shaving and network relief; resilience; customer participation	Medium–High (depends on tariff design)	Interconnection rules; reverse power flow; metering; cybersecurity	Clear compensation mechanism; smart metering; feeder hosting capacity planning	Peak reduction, feeder load, self-consumption rate
PV + BESS hybrids (co-located)	Shift energy to evening peak; reduce curtailment; provide fast grid services	Medium–High (rapidly scaling)	Upfront capex; battery lifecycle and heat management; revenue stacking rules	Hybrid procurement windows; performance guarantees; O&M standards for batteries	Discharge at peak, cycles, availability, curtailment avoided
CSP (thermal storage) / PV–CSP hybrids	Dispatchable renewable capacity; evening supply; grid adequacy	Medium (site-specific)	Higher capex; water/HTF constraints; bankability vs PV	Targeted use where firm capacity is valuable; technology risk sharing	Firm capacity, dispatch hours, LCOE + system value
Demand response (cooling + industrial loads)	Align demand with solar; reduce peak capacity needs; lower curtailment	Medium (program design-dependent)	Customer participation; measurement & verification; equity issues	Tariff/market incentives; automated control pilots; M&V protocols	MW shifted, event performance, persistence
VPP/microgrids + digital aggregation	Coordinate DERs; local balancing;	Medium (fast learning	Interoperability; data quality;	Standards + secure platforms; phased	DER participation,

	bi-directional participation; resilience	curve)	cybersecurity; governance	pilots; audit trails	curtailment reduced, reliability metrics
Solar-to-hydrogen (flexible electrolysis)	Absorb surplus solar; decarbonize industry; potential export value chain	Medium (early scale-up)	Water supply; electrolyser capex; offtake uncertainty; grid impacts	Co-optimised siting; flexible operation; contracts for offtake	kWh/kg H2, utilization, emissions intensity
Grid reinforcement & transmission build-out	Unlock hosting capacity; reduce congestion; connect new projects reliably	Medium–High (but long lead times)	Permitting; long equipment lead times; cost recovery	Forward planning; supply chain risk management; streamlined approvals	Connection time, congestion hours, outages

VII. POLICY AND MARKET DESIGN PROSPECTS

7.1 Targets to Translate into Bankable Projects

In order for the impact of the investment targets to be felt, it is important to note that there is a need to ensure that there is a translation of the targets into projects that can be banked for investment. The Saudi Arabia policy signals through the SGI and the report on the Vision 2030 can be useful in ensuring that there is a reduction in the finance costs and the policy risks for the projects that can be aligned to the policy signals.

7.2 Grid Planning and Code Compliance for Inverter-Based Resources

In order for the high solar futures to be realized, it is important to note that there is a need to ensure that there is a modification to the grid planning approaches. This includes hosting capacity, fast interconnection, and curtailment management, among other grid planning approaches. The future prospect is the inverter-based resources that can be useful in providing support and ride-through using the controllers.

7.3 Localization as a Strategic Lever for the Saudi Economy

In order for the Saudi industry to benefit from the localization of the solar industry, it is imperative to note that there is a need to ensure that there is an offer of employment and skills and stimulation of other sectors of the Saudi industry, including structures, assembly, O&M, and components, among other sectors of the Saudi industry. The future prospect is the quality-based localization, which will help to reduce the tendency to sacrifice the quality of the solar industry for the sake of the Saudi industry.

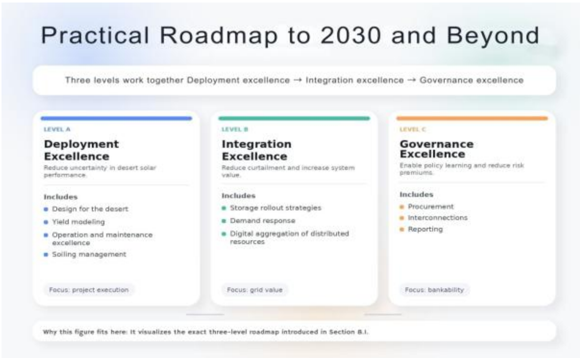
7.4 Solar as an Enabler of New Net-Zero Value Chains

Solar can be used to enable the electrification of industry and hydrogen production by electrolysis. Hydrogen can be used as both a new export product and a seasonal storage option in a net zero future. The vision for the future should be the coordinated rollout of solar and electrolysis, including water supply infrastructure, to prevent new bottlenecks.

VIII. STRATEGIC ROADMAP AND RESEARCH AGENDA

8.1 A Practical Roadmap to 2030 and Beyond

The proposed roadmap based on the review should be developed to have three levels. Level A should be deployment excellence, which will include excellence in design for the desert, yield modeling, and operation and maintenance excellence to reduce uncertainty, especially soiling management [11-13]. Level B should be integration excellence, which will include rollout strategies for storage and demand response to reduce curtailment and increase value, especially digital solutions to aggregate distributed resources [15]. Level C should be governance excellence, which will include procurement, interconnections, and reporting to facilitate policy learning and reduce risk premiums [2-5].



8.2 Priority Research Gaps

Firstly, long-term operating data for the Kingdom of Saudi Arabia for the dynamics of soiling, degradation, and cleaning costs should be obtained and made available for future research in a standardized manner. Secondly, the results of the integration studies should include the quantification of the risks of curtailment for different expansion cases of the transmission and storage infrastructure, as well as the evaluation of the ancillary service value of inverter-based resources. Thirdly, the results of the logistics-related studies should include the evaluation of the impact of procurement rates, port and inland transportation capacity, and quality assurance on time to COD and tariffs. Fourthly, the results of the studies should include the evaluation of the potential of decentralized coordination, for example, in the form of VPP-like aggregation of distributed PV, storage, and flexible demand for utility-scale expansion to meet net zero pathways while preserving cybersecurity and governance requirements [15].

IX. CONCLUSION

The future prospects for solar energy in meeting Saudi Arabia's net-zero and Vision 2030 targets are promising but conditional. The resource advantage is obvious. The key conditions for meeting the targets lie in execution discipline and capability for integration. From the lessons of the period from 2020 to 2025, it has become obvious that performance issues in the desert environment, like soiling and cleaning economics, need to be considered as important aspects in the design and O&M of solar power plants and not as secondary aspects [11-13]. At the system level, storage, demand response, and digital aggregation have become key determinants in the ability to convert solar power into useful and valuable energy while minimizing curtailment as the share of solar energy increases in the energy mix [15]. In short, solar energy has the potential to be a key driver for Saudi Arabia's energy transition to net-zero emissions. However, to achieve the targets set by SGI and Vision 2030, a coordinated effort to build solar capacity, engineer the solution to address the realities of the desert environment, and integrate the solution into the energy system while learning from experience to make each new round of procurements more reliable and lower-risk than the last one is necessary.

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