

Integration of Renewable Energy Sources into Saudi Smart Grids: Challenges, Optimization Strategies and Future Opportunities

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Abstract- Saudi Arabia is making the shift from a centrally controlled electricity system that is based on hydrocarbons to one that is digitally coordinated, in which large-scale solar and wind power, distributed energy resources, storage systems, flexible demand, and power-electronic interfaces interact throughout both the transmission and distribution networks. This change results in a systems issue rather than just a problem relating to power generation: it is necessary to forecast and balance the variability, to manage the low-inertia characteristics, to respect the network's capacity limits, and at the same time to ensure that the increasingly digital control systems remain interoperable and secure. This review carefully brings together peer-reviewed evidence published between 2020 and 2025 in order to look at the engineering, operational and governance needs for incorporating renewable energy into Saudi smart grids. Thirty studies verified by DOI were chosen using a structured process for evidence synthesis, combining research that is specific to Saudi Arabia with internationally applicable work on optimal power flow, demand response, energy storage, grid-forming control and learning-based optimisation. The evidence shows that no single technology can solve the issue of integrating renewables. Real advances require coordinated forecasting, scheduling that takes uncertainty into account, storage and demand flexibility, improved grid-code functions, management of distributed resources and validated real-time optimisation. Key priorities in Saudi Arabia include providing frequency support during times of low demand, using climate considerations in the modelling of assets, ensuring observability of the transmission and distribution networks, achieving interoperable control of distributed energy resources and carrying out a staged rollout of grid-forming capabilities. The review suggests an integrated architecture together with a transition roadmap that connects the physical assets, digital intelligence, market signals and resilience controls. Future research should move from isolated test systems to systems that are calibrated for Saudi conditions, involving cyber-physical and hardware-in-the-loop validation and including clear reliability, economic and security metrics.

I. INTRODUCTION

The transition in Saudi Arabia towards electricity production is now at a stage where renewable energy must be incorporated as an active part of the country's power system rather than being seen as a set of independent projects. Solar photovoltaic resources are particularly appealing due to the high level of solar irradiation, while wind resources offer both spatial and temporal complementarity. The current policy stance also aligns with the broader goals of economic diversification and decarbonisation. Recent reviews carried out in Saudi Arabia indicate that the rollout of renewable energy, the modernisation of the smart grid, energy storage and energy-efficiency initiatives are becoming more closely linked in national planning. A more focused conceptual review in Saudi Arabia also states that the shift involves the need for the simultaneous development of smart energy, communication and information systems, since relying solely on expanding generation capacity is not sufficient to reliably absorb variable power sources.

The technical aspects of integration are difficult since the output of solar and wind energy varies from minute to minute, hour to hour and from season to season, whereas the traditional power grid was built around controllable synchronous generation and mainly involved one-way power flows. An increased proportion of inverter-based resources can lead to a decrease in effective system inertia, change fault behaviour, introduce difficulties relating to voltage control and result in a greater need for fast measurements and communication. Broad-scale studies in the Gulf region also point out that regulatory consistency, the design of investments, market structure and technology readiness are obstacles which can delay the implementation of projects that are technically feasible. In the case of Saudi Arabia, these

problems are compounded by the sharp demand for cooling during the summer months, the geographical concentration of load centres, the existence of long transmission corridors, exposure to dust and heat, and the rapid expansion of the digital grid infrastructure. As a result, successful integration will require a range of engineering and institutional measures rather than just one optimisation algorithm or a single storage technology.

The relevant solution families are outlined in the literature: studies specific to Saudi Arabia indicate possibilities for reducing emissions and reorganising operations, whereas more recent reliability analyses look at the impact of planned expansions of renewable energy on the behaviour of the grid. An analysis in the frequency domain of the Saudi power system reveals that a high level of inverter-fed renewable energy can seriously impair the frequency response after a disturbance, especially when the load is low, and that combined battery storage can offer compensating support. At the distribution level, interoperability standards and microgrid requirements become significant as distributed photovoltaic systems, storage facilities and flexible demand increase. These results lead to a review that connects the national context with modern power-system optimisation instead of addressing renewable energy resources, smart grids and control methods in isolation.

The paper therefore looks at the integration of renewable energy as a problem involving the coordinated optimisation of cyber and physical systems. It identifies the difficulties that arise from resource variability, network physics, converter-dominated dynamics, climatic conditions and digitalisation; assesses the advantages and limitations of deterministic, stochastic, robust, heuristic and learning-based optimisation methods; and points out future opportunities that are appropriate for the Saudi operating environment. While the focus is not on listing projects, it is on combining the mechanisms by which an increase in renewable energy changes the requirements of the system and on converting international technical advances into priorities that can be tested on Saudi power networks.

II. AIM, OBJECTIVES AND REVIEW QUESTIONS

This review seeks to produce a synthesis that is based on technical considerations of how the smart grids in Saudi Arabia can deal with the growing amount of power generated by solar and wind sources while at the same time maintaining reliability, economic efficiency and cyber-physical resilience. The analysis is intentionally more focused than a general examination of Saudi Arabia's energy transition since it looks at the electricity network and the range of operational decisions needed to integrate variable and distributed resources.

The review is based on five objectives. The first of these is to identify the integration constraints specific to Saudi Arabia in both the transmission and distribution systems, covering low-inertia operation, voltage control, climate exposure and observability. The second objective is to compare the various optimisation methods used in renewable scheduling, optimal power flow, storage dispatch and demand response, with a focus on the way each one handles uncertainty and network constraints. The third deals with the assessment of flexibility resources, especially battery storage, controllable demand, electric-vehicle charging and smart inverters, treating them as complementary services rather than as interchangeable ones. The fourth looks at the digital and governance conditions needed for scalable coordination of distributed resources, including interoperability and cybersecurity. The fifth consists of developing a phased research and deployment programme that connects short-term grid reinforcement with longer-term autonomous and grid-forming capabilities.

The following four questions arise out of these objectives: what technical constraints will be most important as the level of renewable energy penetration increases in Saudi networks; which optimisation methods are most appropriate for various timescales and degrees of uncertainty; how storage, demand flexibility and converter controls should be co-ordinated rather than optimised separately; and what evidence gaps need to be filled before advanced control methods can be relied upon in operational Saudi grids?

III. REVIEW METHODOLOGY

In order to carry out a focused review rather than a free-running narrative survey, a structured approach to evidence synthesis was adopted. The time frame for the evidence was restricted to the period 2020 to 2025 so that the synthesis would correspond to the current state of converter-based generation, storage, digital control and Saudi policy conditions. The final collection includes 30 peer-reviewed studies, each having a resolvable digital object identifier. The potential literature was gathered from three key contemporary studies and by carrying out targeted, structured searches in scholarly databases, using combinations of terms relating to Saudi Arabia, smart grids, the integration of renewable energy, photovoltaic generation, wind power, battery energy storage, demand response, optimal power flow, inverter-based resources, grid-forming control, distributed energy resource management and cybersecurity. Before being included, the bibliographic metadata and the DOI strings were verified against the records of the publishers or institutions.

To be eligible, a study had to be directly relevant to at least one of the six analytical themes: the context of the Saudi electricity system; the requirements for integrating renewables; frequency and voltage stability; the provision of flexibility through the use of storage or demand; optimisation and intelligent control; or digital interoperability and security. Studies were excluded if they were outside the date range, had not been peer reviewed, were only very loosely related to grid integration, or presented evidence that had already been covered by a more comprehensive study. When it came to making claims about the Saudi context, priority was given to research that was specifically about Saudi Arabia, while international studies were kept in if they dealt with control mechanisms that are transferable and have not yet been widely validated on Saudi networks. This approach ensures that results obtained from generic test feeders are not presented as evidence of actual performance in Saudi Arabia.

The evidence provided was qualitatively categorised according to decision timescale, the type of controlled asset, the way uncertainty was treated, the form of the

network representation, the performance objective and the validation environment. The optimisation studies were divided into those based on deterministic mathematical programming, stochastic or robust optimisation, metaheuristic multi-objective methods, model-predictive control and data-driven or reinforcement-learning approaches. The grid-support studies were also classified by the type of service they provided, namely energy balancing, voltage control, frequency support, congestion management or resilience. The synthesis then looked not only at the benefits that had been reported but also at the assumptions which limit the transferability of the results, such as perfect forecasts, simplified network models, stationary operating distributions or unconstrained communication.

The methodological quality was assessed by means of four questions: whether the study presented a problem formulation that could be reproduced; whether there had been explicit reference to physical or operational constraints; whether the uncertainty had been represented in a way that was consistent with the claimed application; and whether the validation had been sufficiently transparent to allow an interpretation of the performance. Since the collection includes reviews, simulations and case studies which have different aims, no numerical score for quality was assigned. The approach thus enables a critical comparison without misleading precision when ranking studies against one another. The key limitation of this method is that by limiting the evidence to 30 recently published papers with verified DOIs it gives greater weight to depth and traceability than to comprehensive bibliometric coverage; this limitation is discussed again in Section 9.

IV. SAUDI SMART-GRID CONTEXT AND INTEGRATION REQUIREMENTS

The challenge posed by integrating renewables in Saudi Arabia starts with the question of scale and the way in which the network is structured. Large renewable energy projects are able to feed in considerable amounts of power at sites selected on the basis of the quality of the resources and the availability of land, rather than according to the historical pattern of electricity demand. Moreover, rooftop and smaller community photovoltaic installations can turn passive

distribution feeders into bi-directional networks. This results in two separate requirements: transmission planning must deal with the long-distance transfer of power, congestion, and overall system balancing, while distribution operations must build up the ability to monitor and control resources that are located behind customer meters. The smart-grid architecture therefore has to include coordinated layers for sensing, forecasting, dispatching, protection and for receiving market or tariff signals, not rely on a single central controller.

The fact that solar energy is dominant also leads to a particular temporal issue. Since there is a high level of production during the day, net demand falls and the need for ramping increases around sunset, while in summer the heavy cooling requirements can cause peaks to occur during times when photovoltaic output is decreasing. The evaluation of rooftop solar in NEOM shows how important it is to match the local generation pattern to residential demand rather than assuming that a balance of annual energy consumption means that operational adequacy has been achieved. Similarly, when expanding utility-scale photovoltaic capacity attention must be paid to heat, soiling, equipment derating and maintenance since the nameplate capacity does not directly translate into dispatchable output under desert conditions. Wind can help to spread out the output profile, but its variability introduces an additional element to forecasting. The appropriate planning criterion is therefore not just the amount of renewable capacity; it is the dependable flexibility that is available when there is a divergence between renewable output and demand.

The more synchronous generation is replaced, the more important system dynamics become. An analysis of frequency stability in Saudi Arabia shows that a high level of inverter-fed renewable energy can lead to deeper frequency excursions following disturbances, particularly when the load is light. The fact that this is so does not mean that the level of renewable energy

integration has a fixed technical limit; rather, it means that the system services which have hitherto been provided implicitly by synchronous machines now have to be obtained or deliberately engineered. Contributions can be made by fast battery response, synthetic inertia, frequency-responsive demand, advanced inverter functions and grid-forming controls, but the value of these measures depends on location, the state of charge, control coordination and the use of credible disturbance models.

The same reasoning holds true in the case of voltage and protection: when distributed photovoltaic power is generated there can be overvoltage on lightly loaded feeders, and long transmission links need reactive-power capability as well as fault-ride-through behaviour that is in keeping with system requirements. As shown by international integration reviews, voltage regulation, frequency regulation, reactive support, ride-through and power quality make up a group of interconnected connection requirements. The standards for use in Saudi Arabia should therefore be based on the measured strength of the system and the level of renewable energy deployment, not regard compliance as a fixed checklist.

In the end, digitalisation alters the nature of potential failures. Although advanced metering, automated substations, distributed resource controllers and cloud-edge analytics improve both observability and controllability, they also lead to a reliance on data quality, accurate time synchronisation, the availability of communication links and authenticated control. In order for thousands of devices to be able to provide coordinated grid services, distributed energy resource management needs to make use of interoperable protocols and include layered security. The key integration requirement is thus architectural in character: physical flexibility, converter capability and digital intelligence must all be designed as part of a single operating system.

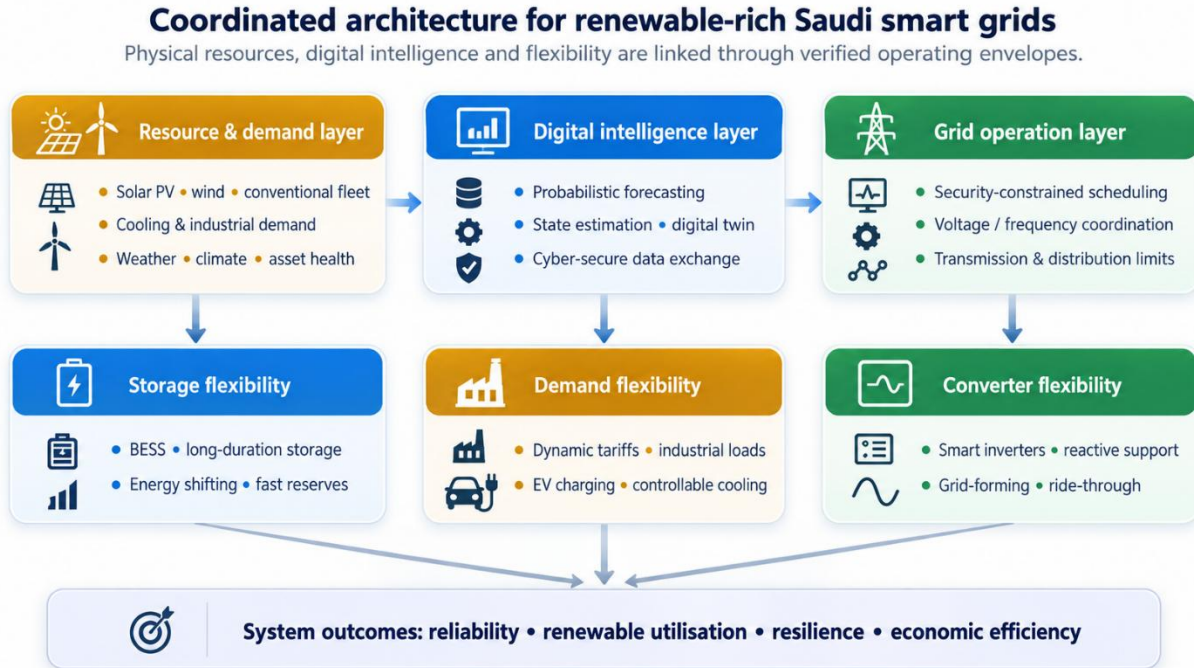


Figure 1. Integrated architecture for coordinating renewable generation, digital intelligence and system flexibility in Saudi smart grids.

V. KEY CHALLENGES FOR RENEWABLE INTEGRATION

The main difficulty lies in the uncertainty that occurs on various timescales. Mistakes made a day in advance have an impact on unit commitment and the acquisition of reserves; intra-hour errors affect the balancing process; and fluctuations that occur every second to second interact with the frequency and voltage control systems. Although a deterministic schedule derived from a single forecast may be economically appealing, it proves to be fragile if the forecast error is significant. On the other hand, having too large a reserve margin reduces the economic value of renewable power generation. For this reason Saudi planners need probabilistic forecasts covering solar irradiance, temperature, wind, demand and the correlated regional errors, along with reserve policies which convert forecast uncertainty into operational headroom. This problem is particularly significant when large projects experience similar weather conditions, since geographically correlated output can invalidate the assumptions that are based on independent fluctuations.

The next problem is operating in a low-inertia environment with a high proportion of converters. Traditional synchronous generators provide stored rotational energy and produce fault current in a well-known manner. In contrast, inverter-based resources separate the primary energy from the grid frequency unless the control systems intentionally replicate the necessary support functions. According to the simulations carried out in Saudi Arabia, the frequency performance may get worse as the amount of power fed in by inverters increases, while more comprehensive reviews point to grid-forming converters as a promising solution for establishing both voltage and frequency in weak or low-inertia systems. However, the introduction of grid-forming converters is not something that can be switched on with a software setting: the interactions between the controls, the current limits, the coordination of protection measures, and the stability when a mix of different technologies are involved all have to be validated at the system level.

Thirdly, distribution networks are limited by their hosting capacity. If there is a high level of photovoltaic generation while at the same time local demand is low, this can cause the voltage to rise and result in reverse

power flows in the feeders. While battery systems can take in the excess energy, their state-of-charge limits mean that they cannot be regarded as being available every time a voltage problem occurs. Studies using reinforcement learning on distributed batteries illustrate the importance of coordinated state-of-charge management for alleviating overvoltage. Although smart inverters can provide reactive power quickly, relying on them repeatedly for reactive support can lead to increased losses or to a restriction of active-power capability. Hosting capacity should therefore be considered a dynamic attribute, influenced by inverter settings, storage state, flexible demand and network reconfiguration, rather than being treated as a fixed megawatt threshold.

Fourthly, the conditions in desert areas lead to a difference in performance between generic models and those used in Saudi operations. The high ambient temperatures have an impact on the efficiency of photovoltaic systems, accelerate battery ageing and reduce the thermal margins of the power electronics, while the build-up of dust alters short-term production and increases the need for maintenance. Since dispatch, state estimation or learning algorithms are trained using idealised equipment curves, they may give an incorrect estimate of the available flexibility. Climate-aware degradation and thermal limitations should therefore be included directly in the optimisation, especially in the case of batteries that are expected to provide both energy arbitrage and fast ancillary services.

Fifth, there can be conflicts between economic and reliability objectives. A storage dispatch aimed at

minimising cost might cause a battery to be depleted before a contingency occurs; minimising curtailment of renewable energy can lead to increased congestion; and aggressive demand shifting may result in rebound peaks. The literature on multi-objective optimisation stresses the importance of highlighting such trade-offs rather than incorporating them into an opaque weighted sum. In the case of Saudi Arabia, additional factors include tariff reform, changing market arrangements, and the presence of large industrial loads whose flexibility could have high value for the system. If flexible resources are expected to keep reserves rather than maximise short-term energy revenue, then reliability services must be properly valued.

The sixth issue concerns digital interoperability and security. In order for a smart grid to coordinate distributed resources it has to pass on measurements, forecasts, prices and control commands beyond the boundaries of various organisations. Although research into DER management points to the importance of common communication standards and hierarchical control, it also lists cyberattacks, unauthorised control and data compromise as serious risks. This leads to a design principle with practical implications: when communications fail, critical control should be able to degrade safely and optimisation must take into account the level of confidence in the data rather than assume that the telemetry is perfect. Relying solely on centralised intelligence is not enough; secure local fallback control and auditable command hierarchies are necessary if resilience is to be achieved.

Table 1. Principal renewable-integration challenges and priority responses for Saudi smart grids.

Integration challenge	Mechanism in Saudi context	Operational consequence	Priority response
Variable solar and wind output	Correlated weather, sunset ramps and changing cooling demand	Reserve needs, curtailment and ramping stress	Probabilistic forecasting plus uncertainty-aware dispatch
Low-inertia operation	Displacement of synchronous generation by inverter-based resources	Larger frequency deviations after disturbances	Fast BESS response, synthetic inertia and staged grid-forming control

Integration challenge	Mechanism in Saudi context	Operational consequence	Priority response
Voltage and hosting capacity	Bidirectional feeder flows and high PV output during light local load	Overvoltage, reactive-power demand and constrained PV hosting	Smart inverters, coordinated BESS and dynamic hosting-capacity assessment
Desert operating conditions	High temperature, dust, thermal derating and accelerated ageing	Forecast bias and reduced available flexibility	Climate-aware equipment models and health-constrained optimisation
Network congestion	Resource-rich sites may be remote from major load centres	Transmission bottlenecks and renewable curtailment	Security-constrained OPF, storage siting and transmission reinforcement
Digital dependence	Growing AMI, automation and distributed-resource control	Exposure to latency, data corruption and unauthorised control	Interoperable DERMS, segmented security and safe local fallback

VI. OPTIMISATION STRATEGIES FOR RENEWABLE-RICH OPERATION

Optimisation provides the decision layer that converts forecasts, network constraints and flexibility into schedules or controls. Deterministic mathematical programming remains useful for planning and day-ahead dispatch when forecasts are sufficiently accurate and network equations can be represented tractably. Linear or mixed-integer formulations can coordinate unit commitment, battery schedules, curtailment and demand shifting with transparent constraints. Their principal strength is interpretability: operators can identify binding limits and reproduce decisions. Their weakness is sensitivity to forecast error and model complexity, particularly when alternating-current network equations, discrete controls and degradation are represented simultaneously.

Stochastic and robust approaches address this weakness from different directions. Stochastic optimisation assigns probabilities to scenarios and seeks decisions that perform well across expected outcomes; robust optimisation protects against specified uncertainty sets without requiring exact probability distributions. For Saudi applications, a hybrid architecture is attractive: scenario-based day-ahead scheduling can represent correlated solar, wind and demand uncertainty, while robust reserve constraints protect against forecast tails or

communication loss. The important design question is not which approach is universally superior, but whether the uncertainty model matches the decision horizon. Overly conservative uncertainty sets can strand renewable energy, whereas narrow scenario sets create false confidence.

Multi-objective and metaheuristic methods are valuable when the problem includes non-convex design variables or competing objectives. A 2020 smart-grid optimisation study demonstrates a multi-objective genetic approach that jointly considered operating cost and carbon emissions and coupled renewable uncertainty with demand response. Wider review evidence shows that hybrid energy-system design increasingly balances cost, emissions, reliability and grid dependence. For Saudi planning, such methods can support storage sizing, renewable siting and microgrid design, but they need careful convergence testing and constraint handling. A numerically good Pareto front is not sufficient if candidate solutions violate realistic network, reserve or equipment limits.

Model-predictive control provides a bridge between scheduling and real-time operation. It repeatedly solves a finite-horizon optimisation using updated measurements and forecasts, which is well suited to batteries, flexible loads and microgrids. Its rolling horizon can recover from forecast errors more gracefully than a fixed day-ahead schedule. The

limitation is computational scaling as network size, nonlinear constraints and uncertainty scenarios grow. This makes hierarchical decomposition important: local controllers can manage fast device dynamics while a supervisory layer sets feeder or system targets. Data-driven and reinforcement-learning methods address situations where explicit models are incomplete or repeated optimisation is too slow. Real-time optimal-power-flow studies show that deep reinforcement learning can map system states to control actions with very low online computational burden. Battery control with a safety layer has achieved near model-predictive cost performance while enforcing network constraints, and Saudi-affiliated microgrid research demonstrates deep Q-network scheduling under stochastic load, generation and price signals. More complex studies coordinate wind, photovoltaic generation, electric vehicles and dispatchable resources, while graph-based

reinforcement learning exploits network topology for active-distribution scheduling.

These advantages do not justify unconstrained deployment. Learning policies can fail under distribution shift, rare disturbances or corrupted measurements. Safe application requires offline training on Saudi-calibrated scenarios, explicit constraint layers, stress testing, explainable fallback logic and operator override. Recent work on autonomous active-power dispatch [27] and intelligent grid operation suggests that learning is most credible when embedded within physics-based boundaries rather than replacing network models entirely. Accordingly, the strongest optimisation architecture is hybrid: mathematical optimisation establishes secure operating envelopes; predictive models update uncertainty; and fast learning-based controllers act within verified limits.

Table 2. Comparative suitability of optimisation strategy families for renewable-rich grid operation.

Strategy family	Best-suited decisions	Uncertainty treatment	Key strength	Main limitation for Saudi deployment
Deterministic LP/MILP/NLP	Day-ahead dispatch, unit commitment, storage schedules	Single forecast or reserve margins	Transparent constraints and reproducible solutions	Can be fragile to renewable and demand forecast error
Stochastic / robust optimisation	Reserve, commitment and congestion under uncertainty	Scenarios, probabilities or uncertainty sets	Explicit treatment risk	Scenario growth or conservatism can raise cost
Multi-objective metaheuristics	Sizing, siting and non-convex design trade-offs	Usually scenario or sampled uncertainty	Handles competing objectives and discrete designs	Convergence and feasibility require careful validation
Model-predictive control	Rolling storage, microgrid and flexible-load control	Repeated forecast updates	Corrects schedules as conditions change	Computational burden increases with network detail
Reinforcement / graph learning	Fast OPF, device control and active-network scheduling	Learns from simulated or historical state distributions	Very fast online response	Distribution shift, explainability and safety constraints
Hybrid physics + learning	Real-time control inside security envelopes	Forecast uncertainty plus learned policies	Combines speed with explicit physical limits	Needs high-fidelity training and independent safety validation

VII. COORDINATING FLEXIBILITY:
STORAGE, DEMAND AND INVERTER
FUNCTIONS

Energy storage is usually seen as the standard solution to the variability of renewable energy, but its value varies according to the service for which it is scheduled. Batteries are capable of shifting solar energy, giving rapid frequency response, controlling feeder voltage, helping to implement black-start strategies and reducing curtailment. These different services compete for both power and energy capacity. A battery that is kept nearly at full charge may not be able to take in excess power from photovoltaics; a battery which is deeply discharged will have only limited capacity to increase its output; frequent cycling at high power levels may speed up its degradation. Therefore, evaluations of the integration of storage systems emphasize the importance of linking the technical characteristics of the storage to the requirements of the grid services rather than simply sizing the storage according to its annual energy output.

The evidence from Saudi Arabia backs this idea that the service is based on supply. Studies looking at frequency show that aggregated battery responses are effective at counteracting the decrease in inertial response, and a study concentrating on NEOM involves combining storage sizing, dynamic tariffs and demand-side management in order to enhance the reliability and economic viability of renewable systems. These applications operate on different timescales and so should not be optimised separately. A practical scheduling hierarchy should set aside a quick-response power range for use in frequency and voltage support, assign an energy range for intraday balancing, and then dynamically adjust both of these in accordance with forecast risk and the condition of the batteries.

The need for flexibility can mean that the amount of storage needed for the same level of renewable energy integration is reduced. The cooling demands in Saudi Arabia, together with the country's water-related infrastructure and large industrial processes, involve potentially valuable demand that can be controlled, as long as comfort requirements, process limitations and rebound effects are honestly taken into account.

Demand response is particularly useful when it shifts consumption to times when solar power is readily available rather than just lowering peak demands. The 2020 optimisation study demonstrates how incentive-based demand response can be combined with renewable scheduling and the aim of minimising both cost and emissions. At a national level, tariff signals should be aligned with network conditions in order to ensure that the simultaneous response by customers does not lead to new ramps or local congestion.

Electric vehicles lead to an increase in demand and also offer storage that can be controlled. The timing of their charging can be arranged so as to take in the solar power available during the day or to prevent excessive demand in the evening, and in the future bidirectional operation might be able to provide local support. Nevertheless, since there are mobility requirements the vehicles' availability cannot be guaranteed and the costs associated with battery degradation are the owners' responsibility. Studies of microgrids using electric vehicles show the potential for optimisation, but before the collective flexibility of vehicles can be treated as firm reserve in Saudi Arabia realistic travel patterns, charger locations, distribution limitations and participation incentives will be needed.

The range of features available through smart inverters adds to the flexibility offered. Reactive-power control, voltage support, active-power curtailment and grid-forming modes can react more quickly than central redispatch. Grid-forming capabilities represent a move away from grid-following devices which synchronise with an existing waveform towards controls that are able to set voltage and frequency references. The strategic opportunity for Saudi Arabia should be to coordinate these functions with storage and demand rather than to obtain them separately. A renewable energy plant equipped with battery storage, having grid-forming capability and the appropriate control contract could provide energy, ramping, frequency and voltage services all from the same interconnection, thus increasing the value to the system without assuming that any of the services is unlimited.

VIII. A ROADMAP COMBINING FUTURE OPPORTUNITIES WITH INTEGRATION

The next stage in the development of Saudi Arabia's smart grid has the potential to shift from integrating projects individually to adopting an integrated way of operating. The first chance lies in the establishment of a national renewable-forecasting and uncertainty service which combines satellite data, numerical weather prediction, data from the power plants and probabilistic load forecasting. By using standardised forecast products, the various parties involved—including system operators, market participants and storage controllers—will be able to base their actions on the same uncertainty information. The quality of the forecasts should be assessed according to their operational value, for example in terms of the amount of reserve that can be reduced or the amount of curtailment that is avoided, not just on the basis of statistical error.

A second option is distributed-energy resource management. Since rooftop photovoltaic systems, batteries, controllable loads and charging equipment are becoming more common, the system will require aggregation methods which convert network constraints into actions at the level of individual devices. While DER management systems can offer hierarchical coordination, interoperability and cybersecurity have to be considered from the very beginning. The Saudi pilots should therefore also examine communication latency, loss of connectivity, certificate management, scenarios involving malicious data and local fallback procedures together with economic dispatch. A control architecture is not operationally mature if it functions well only when each message is received correctly.

Third, grid-forming capability should be introduced by means of staged demonstrations in weak-grid areas, at renewable power plants that have storage facilities located at the same site and at islandable microgrids. Research into converters shows that grid-forming control can support systems with low inertia, although the interactions between different vendors' equipment and their protection schemes are still important. The demonstrations should record the frequency nadir, the rate of change of frequency, voltage recovery, current limiting and the transition behaviour in the case of

realistic faults. Procurement specifications can then be developed from references to technology towards those based on measurable dynamic performance.

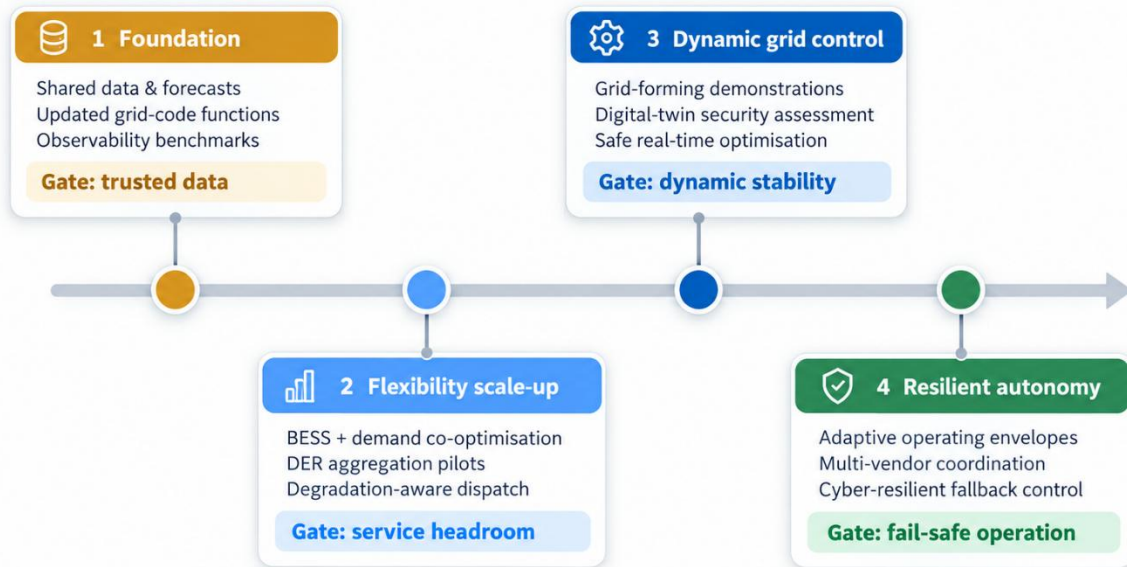
Fourthly, digital twins have the ability to link planning with operation. A network twin that has been validated and which is continuously updated using data from supervisory systems and advanced meters can test various scenarios, such as contingency events, changes due to renewable energy, controller settings and different maintenance states, before any commands are issued. When used with probabilistic forecasting, this type of platform can enable dynamic security assessment and adaptive operating envelopes. The concept also provides a safer environment for training learning-based controllers, since rare disturbances can be simulated repeatedly without having to expose the actual grid.

Fifth, optimisation should incorporate asset health and climate adaptation. Battery temperature, state of health, inverter thermal limits, photovoltaic soiling and transformer loading can be treated as state variables rather than external engineering considerations. The 2024 intelligent-integration review highlights the broader value of advanced sensing and adaptive optimal power flow for extracting capacity while controlling operational risk. In Saudi conditions, this approach could turn environmental constraints into measurable dispatch limits and reduce the difference between modelled and available flexibility.

In the end, the transition provides the chance to redesign the performance indicators. Renewable energy integration should be assessed by means of a balanced dashboard, the dashboard including the amount of renewable energy used, curtailment, reserve adequacy, frequency and voltage excursions, congestion, the risk of customer interruptions, storage degradation, cyber-resilience and total system cost. Relying on a narrow levelised-energy figure may lead to a preference for projects that are cheap at the generator terminal but costly to integrate; in contrast, system-level metrics reward various resources and controls that provide flexibility where it is required. This is essential since the share of renewables increases and the main challenge changes from adding megawatts to securely coordinating them.

Phased roadmap for Saudi renewable-grid integration

Each phase adds capability while retaining explicit reliability and security gates.



Progression principle: scale only after performance is demonstrated under disturbances, climate stress and communication degradation.

Figure 2. Phased deployment roadmap linking capability expansion to explicit reliability and security validation gates.

IX. RESEARCH GAPS, LIMITATIONS AND PRIORITY AGENDA

The most important evidence gap is the limited number of open, high-fidelity studies calibrated to the evolving Saudi network. Many advanced optimisation methods are demonstrated on standard test feeders, which are useful for algorithm comparison but do not reproduce Saudi transmission distances, load concentration, renewable geography, protection settings or climatic derating. The next generation of research should therefore use anonymised but structurally representative Saudi models and publish sufficient assumptions for independent replication. Comparative studies should test the same scenarios across deterministic optimisation, robust methods, predictive control and safe learning rather than reporting performance against weak baselines.

A second gap concerns interactions among control layers. Storage scheduling, voltage control, frequency response, renewable-plant control and demand response are frequently studied separately, yet they compete for the same flexibility. Research should

quantify opportunity costs between services and develop co-optimisation methods that preserve security headroom. Particular attention is needed at low-load, high-renewable conditions identified as sensitive for Saudi frequency performance. Hardware-in-the-loop and controller-in-the-loop experiments can expose time delays, saturation and protection interactions that steady-state optimisation misses.

Third, cybersecurity must be integrated into operational research rather than appended as a qualitative risk. Future DER coordination studies should model delayed, missing and manipulated data; compromised devices; credential failures; and recovery procedures. Security constraints can then be expressed through trusted measurement sets, rate limits, segmented control zones and conservative fallback schedules. The distributed-resource security literature provides a standards-oriented foundation, but Saudi-specific threat modelling and resilience testing remain underdeveloped.

Fourth, flexibility valuations require stronger empirical evidence. Technical potential does not

automatically become dispatchable flexibility. Industrial demand, cooling loads and electric vehicles have participation costs, operational restrictions and behavioural uncertainty. Pilot programmes should measure response persistence, rebound, customer acceptance and locational value. Likewise, storage studies should report degradation-aware costs and service stacking rather than idealised cycling without lifetime consequences.

This review itself has limitations. The 2020-2025 window intentionally excludes older foundational research, and the 30-paper corpus is selective rather than exhaustive. The synthesis also combines Saudi case studies with international technical work; transferability is argued from physical mechanisms, not assumed as demonstrated local performance. Finally, the rapid pace of converter, storage and control development means some implementation evidence will mature after the review period. These limitations reinforce the need for an updateable evidence base linked to Saudi pilot results.

An additional priority is reproducible data governance. Researchers should report temporal resolution, missing-data treatment, forecast horizons, equipment ratings and constraint assumptions, because apparently superior controllers may benefit from hidden information advantages. Shared evaluation protocols should include normal operation, extreme heat, renewable ramps, contingencies and communication degradation. This would allow algorithmic progress to be distinguished from differences in test design.

Equally important, validation should compare centralised and distributed control under identical telemetry constraints. Such experiments can reveal when local autonomy improves resilience, when coordination latency becomes limiting, and which services require system-wide optimisation. The result would be a clearer allocation of intelligence across grid layers.

A priority research agenda follows: establish shared benchmark network models for Saudi renewable-integration studies; build probabilistic climate-aware datasets; compare optimisation methods under common disturbances and communication failures;

validate grid-forming and storage controls in real time; quantify multi-service battery degradation; develop secure DER aggregation pilots; and define system-value metrics that can be used consistently in planning, procurement and operation. Progress on these tasks would convert a fragmented literature into deployable engineering evidence.

X. CONCLUSION

Renewable integration into Saudi smart grids is fundamentally a coordination problem across resources, networks, converters, markets and digital infrastructure. The reviewed evidence shows that expanding solar and wind capacity without equivalent advances in flexibility and control can increase forecasting exposure, congestion, voltage excursions and low-inertia frequency risk. Saudi-specific studies already identify these dynamic challenges, while recent international research provides a growing toolbox of storage coordination, uncertainty-aware optimisation, real-time optimal power flow, reinforcement learning and grid-forming control.

The strongest pathway is not to select one algorithm or technology as the solution. It is to layer capabilities. Probabilistic forecasting should inform reserve and congestion decisions; mathematical optimisation should establish secure schedules and operating envelopes; storage and demand should provide explicitly allocated flexibility; smart and grid-forming inverters should supply fast local support; and distributed-resource management should coordinate devices through interoperable, secure communications. Learning-based control can then accelerate real-time decisions within physics-based and operational safety boundaries.

For Saudi Arabia, the near-term research priority is validation: advanced methods need to be tested against representative network models, desert operating conditions, low-load renewable scenarios, equipment limits and communication failures. Over the longer term, digital twins, adaptive operating envelopes and coordinated grid-forming resources can support a more autonomous system, but only if reliability and cybersecurity remain measurable design constraints. The future opportunity is therefore larger than renewable accommodation. A well-designed smart

grid can convert variable resources into controllable system value, allowing decarbonisation, resilience and economic efficiency to advance together rather than compete.

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