



Original Research Article

Modeling and Simulation of Renewable Energy Integration into Smart Grid Systems in Saudi Arabia

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Abstract: Saudi Arabia is making the transition from an electricity system based mainly on hydrocarbons to one in which solar photovoltaic and wind power make up a much larger share, and this is leading to a demand for simulation tools that are able to account for variability, converter-related dynamics, storage, demand flexibility, and network constraints all within a single, coherent decision-making process. This review brings together peer-reviewed research carried out between 2020 and 2025 on the integration of renewable energy, smart-grid modelling, forecasting, hybrid systems, storage, inverter control, hosting capacity, and applications specific to Saudi Arabia. The findings indicate that no single type of simulation is adequate; quasi-static time-series and techno-economic models are useful for planning and for determining capacity sizes; probabilistic methods are able to take into account uncertainties relating to weather and demand; phasor-domain dynamic models are suitable for studies on electromechanical stability; electromagnetic-transient models are required when inverter controls and interactions with weak grids are the main factors; and data-driven or digital-twin approaches can enhance forecasting and enable online updating of the models. Studies specific to Saudi Arabia show that there is a considerable resource potential but also highlight sensitivity to high ambient temperatures, dust, the uneven distribution of wind resources across the geographical area, demand that is dominated by cooling needs, the economics of storage, and the operating assumptions made in the optimisation process. The review presents an integrated, multi-timescale framework that connects resource forecasting, component models, network constraints, energy management, uncertainty analysis, and validation. It contends that future research into smart grids in Saudi Arabia should go beyond separate optimal-sizing exercises and instead focus on reproducible, grid-aware, uncertainty-aware simulations that have been validated under a range of seasonal and disturbance conditions. The key areas that should receive priority include the assessment of grid-forming inverters, probabilistic hosting capacity, hybrid storage, dynamic demand response, high-resolution resource forecasting, and digital-twin-assisted operation. Pursuing these avenues will help to strengthen the technical credibility of the decisions regarding the deployment of renewable energy while at the same time supporting reliability, flexibility, and economic efficiency.

Keywords: Renewable Energy Integration; Smart Grid; Simulation Modelling; Saudi Arabia; Solar Photovoltaic; Wind Energy; Energy Storage; Inverter Control; Power System Stability.

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1. INTRODUCTION

The electricity transition in Saudi Arabia is particularly significant since the country is experiencing rapidly evolving energy policy, has very good solar resources, is seeing increasing electricity demand, and already has a power system that has traditionally been designed around dispatchable thermal generation. The literature on the national transition identifies solar and wind as the key choices for diversifying the electricity supply and for reducing reliance on fossil fuel generation [1]. Moreover, the engineering effects of having a high share of renewable energy go beyond the amount of capacity installed. The intermittent nature of renewable energy sources changes net-load ramps, reserve requirements, voltage profiles, short-circuit strength, inertia, power quality, and the way in which distribution and transmission assets have to be coordinated. Research into wind integration has demonstrated that uncertainty, reactive-power capability, fault ride-through behaviour, and voltage and angular stability all need to be taken into account together rather than being treated as separate design problems [2]. The same issues arise when a high proportion of inverter-based resources is present, because control interactions and the reduced participation of synchronous machines can render the assumptions used in traditional stability studies invalid [3].

The problem involved at the modelling stage is therefore multi-scale. To estimate energy flows, curtailment, transformer loading, and photovoltaic hosting capacity, distribution planners may have to use simulations based on time series covering a whole year [4]. Power-electronics engineers might need models that show converter controls and protection behaviour on a sub-cycle basis. System operators require forecasts extending from minutes to days, whereas investment studies must make assumptions regarding costs and degradation over a number of years. There is an additional level of complexity when it comes to hybrid renewable systems since storage, demand response, and dispatch rules can significantly affect the capacity needed to meet a given reliability target. This is shown by the literature from Saudi Arabia: combinations of pumped storage and batteries can alter the reliability and use of variable renewable energy supplies [5], and adaptive photovoltaic control can change the amount of energy captured under nonuniform irradiance [6]. It follows that reliable integration studies have to match the fidelity of the model to the physical phenomenon and the decision under examination.

In recent applications from Saudi Arabia, particular attention has been given to optimal sizing, the cost of energy, the net present cost, the renewable

fraction, and the probability of a loss of power supply. Although these criteria are useful, they alone do not indicate whether a given configuration is able to keep voltage, frequency, power quality, and protection performance within acceptable limits when faced with realistic levels of operating uncertainty. One way in which smart-grid ideas help to overcome this shortcoming is by coordinating flexible demand, storage, and distributed generation. It has been shown that demand-response-based sizing illustrates how tariff signals together with customer flexibility can reduce the capacity that is needed for a hybrid system [7], and fuzzy-swarm methods go a step further by combining optimisation with adaptive energy management [8]. A further study of a remote load in Saudi Arabia also demonstrates that the choice of storage and dynamic demand response can make a substantial difference to the economic aspects and the operational balance of the system [9]. Nevertheless, these studies also point out a more general methodological problem: the reliability of the optimisation results depends entirely on the quality of the underlying weather, load, component, network, control, and degradation models.

The review looks at the way modeling and simulation should be organised in order to integrate renewable energy into Saudi smart-grid systems. It does not regard simulation software as something that can be substituted for or treat optimisation as the ultimate objective. Rather, it assesses which types of models are appropriate for use in planning, operation, stability, control, and uncertainty analysis; how the Saudi climatic and demand conditions influence the assumptions made in the models; and how validation can be improved. The review also links the global research findings on power-system stability [10], on renewable energy forecasting [11,12], and on the design of Saudi hybrid systems [13,14] in order to establish a more rigorous approach for future studies.

2. AIM, OBJECTIVES AND RESEARCH QUESTIONS

The goal is to create a critical, context-specific framework for choosing and connecting modelling and simulation methods that are used to integrate variable renewable energy into smart grids. The review is guided by four objectives: to classify the main modelling domains together with their suitable time scales; to examine the impact of uncertainty, storage, demand response, and inverter controls on the results of the integration; to combine existing evidence that is specific to Saudi Arabia regarding hybrid systems and the deployment of smart grids; and to identify the validation practices and research gaps which hinder the transfer from simulation to actual operation. The review seeks to answer the following questions: Which simulation methods are suitable for different decisions relating to the

integration of renewable energy? Which assumptions have the greatest effect on reliability and economic conclusions under Saudi conditions? How should the models depict storage, flexible demand, converter behaviour, and network constraints? What methodological advances are required for smart grids in Saudi Arabia with a high share of renewable energy?

3. REVIEW METHODOLOGY

A structured integrative-review method was chosen since the subject area includes power-system dynamics, renewable forecasting, optimization, energy storage, distribution planning, and country-specific techno-economic studies. The evidence base was limited to peer-reviewed journal articles published between 2020 and 2025 and preference was given to those studies which had explicit models, simulation procedures, optimization formulations, validation steps, comparative benchmarks, or applications that were directly relevant to Saudi Arabia. The potential literature was found by combining terms such as renewable energy integration, smart grid, Saudi Arabia, photovoltaic, wind, microgrid, hybrid renewable energy system, energy storage, demand response, hosting capacity, inverter-based resources, grid-forming inverter, forecasting, uncertainty, optimization, and digital twin. Before being included, the bibliographic information and DOI records were verified against publisher or scholarly metadata.

The review intentionally combines literature on methods from around the world with evidence from the Saudi case. Global studies are kept in place whenever they shed light on a simulation issue which can be directly applied to Saudi power grids, for example in the areas of hosting-capacity assessment, low-inertia stability, forecasting, converter control, storage integration or uncertainty management. Saudi studies are included when they make use of local resource data, local load conditions, grid objectives or deployment arrangements. For instance, the analyses of residential hybrid systems in a number of Saudi cities show the significance of geographical variations in resources and of defining the load [13], while the NEOM case highlights the interaction between simulation, optimization, hydrogen production and multi-criteria decision analysis [14]. The photovoltaic MPPT literature is included since the assumptions regarding energy capture and control at the device level are passed on to the annual energy yield and storage sizing calculations [15].

The quality assessment looked at six aspects: the clarity of the system boundaries; the transparency of the input data and the assumptions; the appropriateness of the temporal and electrical

resolution; the way uncertainty was dealt with; the process of validation or benchmarking; and the completeness of the technical, reliability, and economic metrics. Caution was exercised when studies that relied only on static averages drew conclusions about variable or dynamic operation. In a similar way, optimization studies were regarded as more credible when they included a sensitivity analysis or compared different algorithms rather than giving just a single optimum without carrying out robustness testing. The storage reviews were employed to identify the various services and time scales offered by electrochemical, mechanical, and hybrid storage [16-18], while research into distributed generation helped in the handling of coordinated siting, sizing, and uncertainty [19].

The synthesis is thematically rather than based on bibliometric criteria, which is why no artificial screening figures are given. The ultimate set of sources used for analysis consists of the thirty peer-reviewed articles cited in this paper. The evidence has been grouped into five themes: the Saudi transition context; resource and load uncertainty; component and converter modelling; network, stability, and hosting-capacity simulation; and operational optimisation involving storage and flexible demand. The findings were then associated with different simulation time scales, ranging from electromagnetic transients to seasonal planning. This approach adheres to a key methodological principle, namely that model fidelity should be selected in accordance with the decision and the risk under evaluation, and then connected across scales when a single model is unable to account for all the relevant phenomena.

4. SAUDI SMART-GRID CONTEXT

The integration of renewable energy in Saudi Arabia should be viewed as a system transition rather than as a set of separate solar or wind projects. Although the country has a significant solar advantage, high levels of irradiation do not eliminate operational variability, temperature-related efficiency reductions, performance losses caused by dust, or the geographical mismatch between where electricity is generated and where it is consumed. The smart-grid transition thus requires coordinated development of energy, communication, and information systems. A review concentrating on Saudi Arabia highlights digital monitoring, automation, communication infrastructure, and demand-side management as the key functions that enable the integration of large-scale variable renewables into a more decentralised grid [20]. As a result, the data architecture becomes an integral part of the physical integration process since forecast errors, delayed measurements, poor observability,

and communication limitations can all have an impact on the quality of dispatch and control.

Saudi case studies also indicate that locally optimal configurations are affected by geographical factors and the purpose of the system. In western Saudi Arabia, modelling of hybrid electrification shows that renewable energy sources can reduce reliance on diesel in remote areas, but the feasibility of this depends on the load profile, the sizing of the components, the assumptions regarding fuel, and the resource data [21]. Rural microgrid planning studies likewise show the benefits of using a multi-objective techno-economic design together with sensitivity analysis when solar, wind, diesel, and storage are combined [22]. The insights gained are applicable beyond individual systems since the same balance between variability, storage, dispatchability, and cost is found in grid-connected portfolios.

Storage is so important since it connects the variability of renewable energy to a number of grid services. Reviews of stationary storage highlight the fact that the various technologies differ greatly in terms of response time, power density, energy duration, efficiency, lifetime, and their environmental features [16]. Further evidence that is focused on microgrids indicates that in order for storage to be treated as an operational asset rather than as an ideal energy buffer, the control architecture, the state-of-charge limits, safety, degradation, and coordinated dispatch must all be taken into account [17]. In the case of modelling for Saudi Arabia, this means that the battery capacity should not be optimised merely on the basis of the annual energy balance. The models need to differentiate between high-frequency smoothing, intra-day shifting, reserve, peak reduction, backup, and seasonal requirements, since each of these services has different cycling and economic implications.

Table 1: The renewable-integration challenges specific to Saudi Arabia and the recommended simulation treatment

Saudi integration challenge	Modeling treatment	Recommended metric / stress test	Planning or operational implication
High heat and dust	Temperature-dependent PV efficiency, soiling loss, thermal equipment ratings	Summer peak and high-irradiance seasonal cases	Avoid overstated PV yield and equipment headroom
Solar variability and forecast error	Probabilistic irradiance and forecast-error scenarios	Ramp distributions, reserve and curtailment sensitivity	Size flexibility and reserves against imperfect forecasts
Spatially variable wind resource	Location-specific wind distributions and turbine curves	Multi-site resource scenarios	Prevent national-average resource assumptions
Cooling-dominated demand	Weather-correlated sub-hourly load models	Peak-coincidence and rebound tests	Capture demand-response limits and PV-load coincidence
Low inertia / weak-grid conditions	Grid strength, grid-following and grid-forming controls	Fault, frequency and voltage-disturbance cases	Define inverter requirements and dynamic limits
Storage economics and ageing	SOC limits, efficiency, degradation and replacement	Cycle-throughput and lifetime-cost sensitivity	Avoid low-cost designs that rely on aggressive cycling
Smart-grid communication and flexibility	Latency, availability, customer participation and control hierarchy	Communication-loss and reduced-participation scenarios	Quantify robustness of coordinated demand response

5. MODELING AND SIMULATION FRAMEWORK

This hierarchy also avoids unnecessary complexity in the model since detailed converter or

communication representations are only introduced when their dynamics can actually change the decision that is under evaluation.

Integrated Modeling and Simulation Framework

From Saudi resource data to validated grid-integration decisions

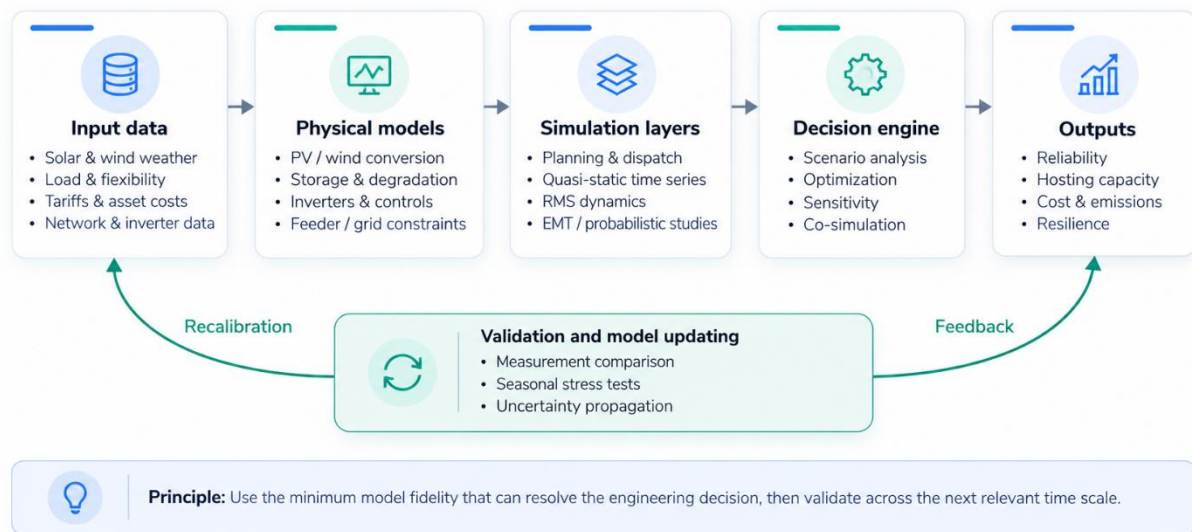


Figure 1: Integrated review-to-simulation framework for renewable-energy integration studies in Saudi smart grids

5.1 Resource, load and forecasting models

Renewable integration begins with the use of time-dependent resource models; for solar simulation one must use irradiance, temperature, module characteristics, conversion efficiency, assumptions concerning soiling, and inverter limits. Wind models require hub-height wind-speed distributions, turbine power curves, assumptions about wakes or availability where applicable, and a method of handling forecast error. Because the outputs of solar and wind power are stochastic, the annual averages are incapable of showing ramps, the coincidence with demand, or the requirement for reserves. It has been demonstrated in reviews of forecasting that machine-learning and metaheuristic methods can improve short-term predictions of renewables on condition that care is taken when choosing the model, when carrying out feature engineering, when using the training data, and when selecting the error metrics [11]. The deep-learning surveys also emphasize that renewable and load forecasting should be evaluated using transparent datasets and a number of different performance metrics rather than just one accuracy statistic [12].

The reason why Saudi Arabia's forecasts merit further consideration is that high solar exposure could create the false impression of low uncertainty. A probabilistic study of solar irradiance in Saudi Arabia demonstrates the benefits of spatiotemporal models in that they preserve the temporal structure when it comes to forecasting and simulating solar resources [23]. Research concerning short-term photovoltaic forecasting also suggests that hybrid data-driven models can improve

predictive accuracy [24]. In the case of integration studies, forecast uncertainty must be taken into account when deciding on dispatch, the state of charge of storage systems, reserve scheduling, curtailment, and the results from the market or tariffs. Although a deterministic 'perfect forecast' scenario remains useful as a benchmark, it should not be the only scenario used when assessing feasibility.

It is just as crucial to carry out load modeling since electricity demand in Saudi Arabia is influenced by the need for cooling, by the daily patterns of occupancy, by the type of building, and more recently by flexible loads such as electric vehicles. At the planning stage, hourly or sub-hourly profiles should be used rather than monthly energy totals. In the case of operational problems, stochastic load scenarios have to be combined with weather data because temperature affects both demand and the efficiency of photovoltaics. Demand-response models must indicate which loads are shiftable, curtailable, or thermostatically controllable, as well as take into account rebound effects, comfort constraints, and customer participation; otherwise the amount of flexibility that the model predicts would be unrealistically high.

5.2 Component, storage and energy-management models

The component models must correspond with the aim of the study; in the case of long-term planning, photovoltaic arrays and wind turbines can usually be represented by validated algebraic performance curves that take into account temperature and availability derating. With regard to

storage systems, the models have to consider charge and discharge efficiencies, power limits, the state-of-charge boundaries, and self-discharge, all of which must be based on the material properties, degradation, and replacement costs. For hybrid storage systems, the rapid fluctuations can be attributed to batteries or supercapacitors while the longer-term energy deficits are assigned to pumped hydro or other long-duration technologies. As is shown in the literature on hybrid pumped-hydro/battery systems, the operational strategy is closely linked to capacity design since different dispatch rules can result in changes to storage utilisation and system reliability [5].

Energy-management systems connect these components. Even though rule-based control is transparent and helpful for benchmarking, model-predictive, fuzzy, or optimization-based controllers are capable of making more effective use of forecasts and information regarding the system's state. Research into demand response in Saudi Arabia shows that dynamic tariffs and adaptive logic can influence load shifting and reduce the amount of renewable and storage equipment that is needed [7,8]. Although these findings are valuable, the flexibility assumptions must be tested under stress. A tariff response based on an assumed elasticity could result in attractive economic outcomes even if it overestimates the real behaviour of customers. Robust studies therefore should vary the elasticity, the participation rates, the forecast error, the storage degradation, and the tariff structure.

When it comes to grid-connected systems, the objective function should not be limited to the cost of energy; multi-objective formulations can consider the net present cost, emissions, the fraction of renewable energy, unmet load, energy not served, curtailment, battery degradation, voltage deviation, losses, and reserve margins. The NEOM analysis demonstrates how multi-criteria methods are capable of identifying configurations that have very similar techno-economic outcomes [14]. Such methods are useful in cases involving conflicting objectives, but it is important that the weighting schemes be clearly reported and tested for sensitivity, since a configuration that seems optimal might simply be a reflection of the analyst's preferences rather than an indication of the system's actual performance.

5.3 Network, hosting-capacity and dynamic models

It is necessary to model the distribution network when the level of renewable energy integration has an effect on voltages, thermal loading, reverse power flow, protection coordination, or power quality. While hosting capacity provides a way

of working out how much distributed photovoltaic generation can be connected before operational limits are reached, the literature shows that the results depend on the definition used, the feeder conditions, the deployment pattern, the load assumptions, and the voltage criteria [4]. For distribution studies in Saudi Arabia, probabilistic or time-series methods for determining hosting capacity are superior to the use of single worst-case snapshots because solar output and cooling demand have a strong temporal structure.

As inverter-based resources replace synchronous generators, frequency response, voltage support, fault behaviour, and control interactions are growing ever more dependent on the settings of the converters. Reviews of grid stability in systems with a high proportion of renewables have pointed out new or more evident phenomena which do not fit well within the traditional electromechanical categories [10]. Research into grid-forming inverters indicates that converter controls can determine the voltage and frequency references rather than merely following the existing grid [25]. Evidence from pilot projects shows that such controls can provide valuable services in weak or low-inertia systems, but field validation is still less advanced than the research carried out by means of simulation [26]. Saudi studies should therefore distinguish between grid-following and grid-forming assumptions and should not regard all inverter-based generation as a general negative load.

One good method is to carry out a quasi-static time-series power flow analysis when looking at annual voltage levels, loading, losses, and curtailment; use phasor-domain RMS models when dealing with frequency, voltage, and electromechanical dynamics on time scales ranging from milliseconds to minutes; and employ electromagnetic-transient models in cases where switching, fast current control, interactions with a weak grid, or protection behaviour are important. It is necessary to have appropriate model interfaces, since the capacity determined by an annual optimization must be passed on to the network and dynamic studies rather than being regarded as technically feasible without further examination. If violations are detected, the sizing optimization should be redone while taking into account the constraints obtained from the network. This iterative coupling process is more reliable than first optimising the generation and then examining how the grid responds.

5.4 Uncertainty, optimization and validation

It is necessary to represent uncertainty explicitly because the decisions involved in integrating renewable energy are influenced by

weather conditions, variations in load demand, price fluctuations, the performance of components, and changes in behaviour. At various computational scales, Monte Carlo simulation, scenario trees, stochastic optimization, and robust optimization are all appropriate methods. Reviews of planning studies concerning distributed generation and storage indicate that coordinated siting and sizing can change considerably when uncertainty and network constraints are taken into account [19]. Sensitivity analysis should therefore be seen as an essential tool for verifying a model, not just as a decorative final step. The key variables to be considered in the Saudi studies are solar irradiance, ambient temperature, soiling losses, wind speed, load growth, discount rate, battery cost, degradation rate, fuel price, tariff design, and demand-response participation.

The optimization algorithm also has to have its performance checked. Even though metaheuristic techniques are capable of efficiently searching nonconvex design spaces, the best objective value which the algorithm has reported does not show that it has reached global optimality or that it is robust from an engineering standpoint. In order to improve its credibility, comparative tests should be carried out, a number of different seeds used, the convergence statistics examined, the constraints checked, and benchmark problems should be employed. As is demonstrated in the literature concerning photovoltaic control, the advantage of combining simulation with experimental verification can be observed when adaptive optimization is applied under changing conditions [6]. The same principle holds true in the case of system-level studies: the output of the optimization process should be verified by means of independent power-flow or dynamic simulation, and where possible actual operating data should be used.

Digital-twin concepts provide a means of reducing the gap between offline models and real-world operation. Electric-grid digital twins include real-time measurements, historical data, system models, analytics, and continuous updates in order to achieve state awareness and prediction [27]. The advantages that such digital twins would offer for the integration of renewable energy in Saudi Arabia would be most evident in situations where high-resolution weather data, inverter telemetry, storage state, feeder measurements, and load data can all be incorporated into a dynamic network model. However, digital twins do not eliminate modeling uncertainty; rather, they place greater emphasis on data quality, observability, synchronization, cybersecurity, and the governance of model updates.

6. COMPARATIVE SYNTHESIS OF EVIDENCE

The literature surveyed indicates that the incorporation of renewable energy into Saudi Arabia has progressed from an examination of its resource potential to more sophisticated approaches involving hybrid optimisation and smart-grid concepts, even though methodological integration has still not been fully achieved. Techno-economic studies are most useful when they consider local weather conditions, realistic load profiles, the limitations of the components involved, and sensitivity analysis. For example, the study of the Taif grid-connected renewable energy project incorporates both solar and wind resources, reliability constraints, economic indicators, and optimisation specifically for a particular Saudi load application [28]. In a similar way, the 2025 evaluation of the Makkah microgrid demonstrates the advantages of comparing grid-connected photovoltaic systems with photovoltaic systems that also include batteries, in terms of cost, reliability, renewable fraction, and emissions [29]. Although these studies provide valuable insights for planning purposes, their results become more practical when they are connected to feeder hosting capacity and dynamic stability analysis.

Five repeated trade-offs in the modelling process are identified in the evidence. The first of these is that there is a conflict between computational tractability and physical fidelity: annual optimisation can examine thousands of different capacity combinations but usually simplifies the converter dynamics, whereas electromagnetic-transient studies include those dynamics but are not economically able to cover decades of weather. The second is that deterministic optimisation is easy to interpret yet tends to underestimate the need for reserves and storage. Third, even though advanced machine-learning forecasts can reduce prediction error they may be difficult to extrapolate in cases of distribution shift, extreme weather, or changing load patterns. Fourth, although storage increases flexibility it also leads to degradation and introduces uncertainty about replacement. Fifth, demand response can reduce the need for capacity, but the extent of this effect depends on assumptions regarding behaviour which are often less well validated than electrical models.

What is provided by these trade-offs is a method that involves carrying out the process step by step instead of relying on a single comprehensive model. In the first stage the Saudi resources and load data should be characterised at an hourly rate or with an even greater level of detail, including the effects of temperature on both demand and generation derating. In the second stage capacity and dispatch optimisation should be performed under a range of different weather, cost, and demand scenarios. In the

third stage the selected configurations should be applied to actual or representative network models so that time-series power flow analysis and probabilistic hosting-capacity analysis can be carried out. In the fourth stage credible cases featuring a high proportion of renewables should be subjected to dynamic simulation, the simulation covering low-inertia conditions, converter control, disturbances, and events that are relevant to protection. In the fifth stage the design constraints should be reviewed in light of any violations and then the economic and reliability impacts should be quantified. Finally, the model should be validated against measured data, results from independent software, hardware-in-the-loop tests, or published benchmark systems, depending on the scale of the study.

It also makes clear the role of smart-grid functionality. Smart grids consist not merely of ordinary networks to which sensors have been added; rather, their value comes about as a result of coordinated measurement, forecasting, communication, optimization, and control. Saudi Arabia's development of its smart grid is thus closely linked to data governance and interoperability [20]. Forecasts have to be incorporated into dispatch

decisions; the controls for storage must take into account the network constraints; flexible loads must respond within realistic limits; and the settings for inverters must be coordinated with the system's strength and with the protection requirements. It is in these areas that co-simulation proves to be useful, since the electrical, communication, market, and control models may need different solvers and time steps.

The literature also indicates that renewable energy integration should be assessed using a range of different metrics rather than relying on a single best measure. While economic indicators such as levelized cost and net present cost are important, they should also be accompanied by figures on renewable curtailment, loss of load, energy not served, battery throughput, voltage violations, frequency nadir, rate of change of frequency, harmonic or power-quality indicators where appropriate, emissions, and resilience measures. A model which manages to keep costs low by depending heavily on frequent imports from the grid, employing aggressive battery cycling, or making use of ideal demand response may fail to achieve the strategic objectives of renewable integration.

Table 2: Modeling and simulation layers for renewable-energy integration.

Layer	Typical time scale	Core model focus	Primary outputs	Main limitation
Resource and load forecasting	Minutes to days	Weather-conditioned statistical/ML forecasting; correlated load scenarios	Forecast distributions, ramps, reserve needs	Data quality and distribution shift
Techno-economic sizing	Hourly to multi-year	Dispatch, storage sizing, capacity optimization, degradation and replacement	LCOE/NPC, renewable fraction, storage size, curtailment	Often simplifies grid dynamics
Distribution hosting capacity	Seconds to annual series	Unbalanced power flow, probabilistic or time-series feeder analysis	Voltage/thermal violations, reverse flow, hosting capacity	Requires credible feeder and adoption data
RMS/phasor dynamics	Milliseconds to minutes	Inverter, machine and controller dynamics around disturbances	Frequency nadir, RoCoF, damping, voltage recovery	Does not resolve switching phenomena
Electromagnetic transients	Microseconds to seconds	Switching converters, fast controls, harmonics and protection interaction	Waveforms, harmonic distortion, control instability	High computational burden
Co-simulation / digital twin	Mixed / online	Electrical, communication and data-assimilation layers	Updated states, predictive control, online decision support	Interoperability, cyber and data-governance demands

Multi-timescale Validation Stack

A layered route from fast converter dynamics to long-horizon planning

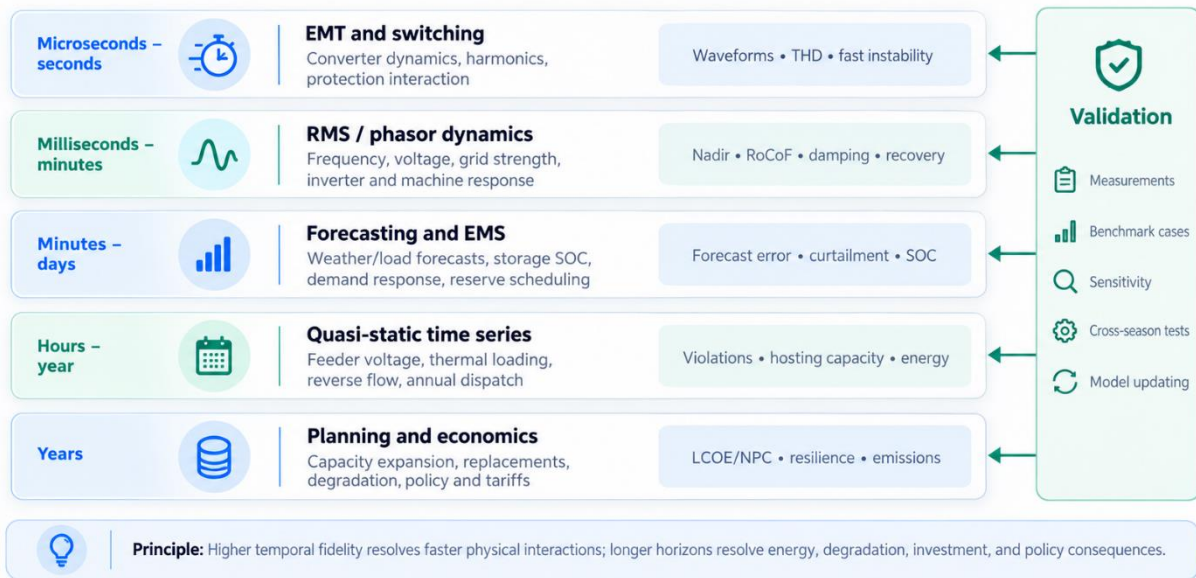


Figure 2: Multi-timescale validation stack linking converter dynamics, grid operation, forecasting, and long-horizon planning

7. RESEARCH GAPS AND FUTURE DIRECTIONS

A significant research gap lies in the lack of integration between planning and dynamic security. In studies of Saudi hybrid systems it is usual to optimise capacities without taking into account detailed constraints relating to grid strength or inverter control. It is necessary in future research to create sequential or co-optimised frameworks in which the annual sizing is constrained by hosting capacity, fault levels, voltage stability, frequency performance and converter limits. Special attention should be paid to grid-forming controls since they may become important as the amount of inverter-based generation increases, although their benefits and risks depend on the network strength and on coordinated tuning [25,26].

Second, the way uncertainty is handled should go beyond conducting sensitivity analyses one factor at a time. Although the solar resources in Saudi Arabia are good they are not perfectly predictable and wind availability varies more from one location to another. Probabilistic resource scenarios should be combined with correlated cooling demand, storage degradation, and forecast error. Although forecasting research has developed increasingly powerful statistical and machine-learning tools [11,12,23,24], integration studies should assess how improvements in forecasting lead to lower reserves, less curtailment, or better use of storage rather than simply reporting the accuracy of the forecasting.

Thirdly, in order to study distribution-level hosting capacity it is necessary to carry out more

locally based research. Since high levels of photovoltaic generation can lead to voltage rises which are specific to feeders, reverse power flow, thermal overload, and protection problems [4], the distribution simulations carried out in Saudi Arabia should make use of a realistic feeder topology, phase imbalance where this is relevant, actual voltage-regulation equipment, spatial PV adoption scenarios, and equipment ratings that are dependent on temperature. The constraints obtained in this way should be used to establish connection rules and to plan targeted reinforcement rather than relying on general penetration limits.

Fourthly, storage modelling should take into account service stacking and degradation. Reviews have indicated that no single technology dominates across all power and energy timescales [16-18]. When considering Saudi applications, batteries, long-duration storage, thermal flexibility, pumped storage where it is geographically possible, and hybrid arrangements should all be compared, using common reliability metrics. Particularly important is degradation-aware dispatch since aggressive cycling can make an apparently low-cost design economically misleading.

Fifth, there is still an uneven level of reproducibility for models. In future studies it is necessary to make public the time resolution, the weather data sources, the method used to deal with missing data, how the load profiles were constructed, the component parameters, the solver tolerances, the optimization seeds, the way the constraints were

formulated, and the validation data. While research into digital twins suggests the use of grid models that are continuously updated [27], reproducibility must come before any real-time advancements. The use of shared benchmark feeders together with openly described Saudi resource-load scenarios would enable competing control and optimization strategies to be compared on a fair basis.

An important sixth issue is the calibration of models when operating conditions are changing rapidly. In studies looking at the integration of renewable energy, network parameters, inverter settings, load composition and the efficiencies of the components are often assumed to be fixed, even though factors such as temperature, the ageing of equipment, updates to controllers, and changes in customer behaviour can cause these quantities to vary over time. This is relevant for use in Saudi Arabia since during periods of very heavy summer demand there will be high output from photovoltaic systems and higher equipment temperatures, conditions which are not captured by the average annual values of the parameters. A more robust procedure would involve separating the estimation of parameters from the simulation of scenarios: first the supervisory, smart-meter, weather and inverter data measured would be used to update the uncertain model parameters, and then the calibrated model would be subjected to standard seasonal and disturbance stress tests. When physical measurements are incomplete, data-driven prediction of parameters can help with this process, on the condition that the relationships that have been learned are constrained by engineering considerations and have been tested beyond the training period [30]. The validation process should not only report the overall energy error but also the errors in voltage magnitude, power flow, ramp rate, state of charge, curtailment and recovery from disturbances. By carrying out cross-validation over different seasons and locations it will be possible to determine whether the model actually generalises or simply replicates one dataset. This kind of calibration practice would also increase the credibility of digital-twin implementations by specifying when a model must be updated, which measurements cause it to be recalibrated, and how uncertainty is incorporated into operational decisions. This method links artificial-intelligence tools with physically interpretable simulation rather than having the latter be replaced by them, and it offers a practical way of moving from offline planning studies to smart-grid decision support that is continuously validated. The benchmark datasets should include metadata on sensor quality, sampling intervals, outages and maintenance events so that the validation process can be audited by different research teams.

8. PRACTICAL AND POLICY IMPLICATIONS

For planners, the main point is that the renewable capacity targets must be turned into grid studies which include specific temporal and dynamic constraints. Capacity expansion, the acquisition of storage, demand-response schemes, and the strengthening of the network should all be regarded as interrelated decisions. Utilities can only obtain value from high-resolution measurement and communication infrastructure when the models used are able to turn the data into verified forecasts, determine dispatch actions, and set network-control parameters. Project developers' techno-economic optimisation should take into account network connection limits and degradation rather than assume that the grid has unlimited flexibility.

Policy design can also have an effect on the outcomes of models. The extent to which flexibility has economic value is determined by tariffs, compensation for exports, rules concerning ancillary services, interconnection requirements, and demand-response incentives. Since studies on demand response have shown that dynamic pricing can substantially change the size of the optimal hybrid system [7-9], the assumptions underlying regulation should be made transparent in scenario analysis. Saudi research and demonstration programmes should require multi-timescale validation for projects based on a high share of renewables: annual assessments of energy and cost, network hosting analysis, and disturbance testing should be regarded as complementary evidence.

9. LIMITATIONS

The review is not a quantitative meta-analysis but rather thematically and methodologically oriented. Since the studies have different objectives, vary in the size of the systems, use different weather datasets, make different assumptions regarding tariffs, apply different reliability criteria, and employ different optimization formulations, the reported numerical results cannot be directly combined. The body of evidence from thirty sources has been deliberately limited to peer-reviewed literature published between 2020 and 2025 and thus does not reflect the complete historical evolution of the theory concerning microgrid control or the integration of renewable energy. The framework focuses on solar energy, wind energy, storage systems, demand response, and inverter-based operation; discussions of detailed transmission expansion, market equilibrium, and cybersecurity models are included only to the extent that they have a direct impact on the simulation architecture.

10. CONCLUSION

The integration of renewable energy into Saudi smart-grid systems involves more than simply

selecting an optimization algorithm or carrying out a simulation of the annual energy balance; the main problem lies in linking the uncertainty of resources and load with the physical characteristics of the components, the behaviour of storage systems, the network constraints, the inverter controls, the flexibility of demand, and the economic objectives over a range of time scales. As the evidence examined indicates, techno-economic optimisation, forecasting, hosting-capacity analysis, dynamic simulation, and data-driven operation address different questions and should therefore be combined rather than replaced one by the other.

Because of this, the suggested order for carrying out the research starts with transparent data preparation, moves on to more detailed model layers only when the decision calls for them, and finishes with independent validation based on measurements, alternative scenarios, or higher-fidelity simulations before any conclusions are broadly generalized.

The combination of Saudi Arabia's excellent solar potential and its increasing ability to manage the smart grid provides favourable conditions for the deployment of renewable energy, but in order to be credible studies must take into account heat, dust, variations in the available resource over space, the impact of cooling on energy demand, the degradation of storage systems, and the imperfection of forecasts. Future research should focus on probabilistic feeder studies, on the validation of grid-forming inverters, on hybrid and long-duration storage, on energy management that takes degradation into account, on coupled planning and dynamic optimisation, and on assisted model updating using digital twins. A well-structured and validated simulation process can convert the potential of renewable resources into investment decisions that are operationally credible, thus helping to create a grid that is not only lower in carbon emissions but also reliable, flexible, observable and economically efficient.

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