

Digital Twin-Based Smart Grid Management Framework for Sustainable Power Infrastructure Development in Saudi Arabia.

Abstract

The power industry in Saudi Arabia is undergoing a transformation from a system in which electricity is centrally dispatched and which is based mainly on hydrocarbons to one that is more varied and incorporates utility-scale renewable energy, distributed resources, storage, digital substations, and control systems that demand ever-increasing amounts of data. This change brings with it a management problem because merely expanding the physical grid is not sufficient to guarantee the continuous monitoring, predictive capabilities, coordination between various assets, and the ability to learn over the lifetime that are necessary in a network with a high proportion of renewables. The article examines digital twin technology as a means of managing the sustainable development of power infrastructure in Saudi Arabia. It carries out a systematic and integrated review of peer-reviewed literature published between 2020 and 2025, drawing on evidence from the fields of digital twin architecture, smart-grid operation, renewable energy integration, microgrids, edge intelligence, cybersecurity, asset management, and studies of Saudi Arabia's energy transition. The review distinguishes between monitoring replicas and operational twins that are capable of achieving state synchronization, forecasting, scenario testing, and controlled feedback. It then proposes a six-layer Saudi Digital Twin Smart Grid Management Framework which links together physical assets, sensing and edge systems, interoperable data services, hybrid grid models, decision intelligence, and governed control. The analysis shows that the value is not primarily in having a visually complete virtual grid but rather in maintaining a reliable alignment between data and models, possessing validated uncertainty, ensuring secure bidirectional interfaces, and making certain that the decision-making authorities assigned are appropriate for critical infrastructure. A step-by-step implementation approach is recommended, progressing from limited operational twins to a coordinated regional federation. The paper concludes that digital twins can only contribute to maintaining reliability, improving the capacity to host renewables, optimising the lifespan of assets, and achieving measurable sustainability when the technical architecture is combined with information security, data governance, a rigorous validation process, and institutional capability.

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32 1. INTRODUCTION

33 Power systems are currently evolving into cyber-physical infrastructure systems in which the
34 quality of their operation depends on the interaction between the physical equipment, the
35 measurement systems, the communication systems, the software, the models, and the ever-
36 increasing use of automated decision-making processes. As a result of this evolution, digital
37 twins have emerged as virtual representations that are constantly updated and which connect the
38 real-time states of the assets with the models, the analytics, and the operational actions. Digital
39 twins are especially important in the case of power systems since a grid is not a single asset but a
40 network that is spread out over a geographical area and whose secure operation necessitates
41 maintaining a balance, keeping the voltage and frequency within limits, respecting the
42 equipment's limits, ensuring proper protection coordination, and preserving resilience even
43 though generation and demand vary continuously.

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45 The literature concerning smart grids shows that edge computing, high-resolution sensing,
46 machine learning, distributed energy resources, and secure communication are already
47 influencing the way power networks are monitored and controlled. A digital twin can integrate
48 these capabilities into a single continuous operational model instead of keeping them as separate
49 digital applications. Consequently, power-system studies describe twin architectures that connect
50 the physical networks, the perception layers, the communication systems, the data services, the
51 simulation models, and the applications employed for condition assessment, forecasting,
52 optimization, and self-healing. However, the potential provided by such a system should not be
53 misunderstood as meaning that increasing the amount of data or having a more detailed model
54 will automatically result in better decisions. A useful grid twin must remain synchronised with
55 physical reality, measure the error of the model, remain computationally responsive, and give
56 recommendations within both operational and cybersecurity constraints.

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58 Saudi Arabia provides a particularly significant case in which to study this technology. The
59 nation is at present boosting its production of renewable energy, modernising its grid

infrastructure, striving to improve energy efficiency, and preparing a broader low-carbon transition strategy. The Saudi smart-grid studies have also highlighted the importance of advanced communications, distributed sensing, and cyber-security. Changes in the amount of renewable energy fed into the system result in modifications to the operating conditions since generation connected through inverters alters the system dynamics, the requirements for forecasting, the need for reserves, and the frequency-response characteristics. As a result, a static planning model is not adequate for a number of the new types of decisions. Operators now need models which can learn from current measurements, predict short-term conditions, evaluate alternative control measures, and keep traceability throughout the asset's lifecycle.

The existing reviews provide a reliable foundation for understanding what digital twins are, the technologies that enable them, their application in the energy sector, the automation of microgrids, and the computing challenges involved. Yet there remains a gap between general technology surveys and an implementation-oriented management framework that is specifically tailored to the development of Saudi power infrastructure. The problem does not merely concern the creation of a digital representation of the Saudi grid; it is about how to govern a continuously evolving set of operational twins so that aspects such as sensing, the models, cyber controls, maintenance intelligence, coordination with renewable energy sources, and sustainability indicators can support decision-making at every level, from that of individual assets up to the system as a whole. To address this gap, this review integrates technical evidence with the requirements associated with Saudi Arabia's energy transition and views the digital twin not just as a simulation product but as a managed decision-making infrastructure.

2. AIM, OBJECTIVES AND RESEARCH QUESTIONS

The aim of this review is to develop a smart-grid management framework that is tailored to the Saudi situation, integrating grid observability, asset-lifecycle intelligence, renewable flexibility, cyber-resilience, and sustainability governance in such a manner as to offer a feasible path for the development of the country's power infrastructure.

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90 The review is centred on five objectives. The first of these is to distinguish between functional
91 maturity and simple digital replication by examining the progress achieved from monitoring
92 stage through to predictive, prescriptive, and coordinated closed-loop operation. The second
93 objective is to combine the different roles of digital twins in the areas of generation,
94 transmission, distribution, microgrids, storage, flexible demand, and their interaction with
95 electric mobility. The third objective consists in identifying the particular requirements that have
96 emerged in Saudi Arabia as a result of the expansion of renewable energy, the country's climatic
97 conditions, the extent of its communications network, its system-security obligations, and the
98 need for institutional coordination. The fourth objective is to look at the data, interoperability,
99 validation, and cybersecurity conditions that are needed for reliable operation. The fifth objective
100 is to propose a staged architecture and an evaluation methodology that can assist in guiding pilot
101 projects, their scaling up, and future research.

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103 **3. REVIEW METHODOLOGY**

104 **3.1 Review design and search scope**

105 An integrative review using a formal approach was selected since the research problem spans a
106 number of fields, including electrical engineering, computing, asset management, energy policy,
107 and the governance of critical infrastructure. A rather limited meta-analysis would not be
108 appropriate since the evidence includes conceptual architectures, laboratory demonstrations,
109 operational case studies, review articles, and analyses of Saudi Arabia's transition, all of which
110 involve different kinds of outcomes. The approach therefore stresses clear source selection,
111 thematic coding, comparing the various studies, and synthesising frameworks. This method
112 corresponds to review practices that involve literature retrieval, thematic analysis, challenge
113 mapping, and the development of conceptual frameworks, without treating studies that are of a
114 different nature as if they were statistically interchangeable.

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The period covered by the main search was from January 2020 to December 2025. The search was carried out using four groups of concepts: those relating to digital twins; terms related to the smart grid, the power system, the distribution network, the microgrid or distributed energy; management functions such as forecasting, state assessment, predictive maintenance, optimization, resilience and cybersecurity; and terms connected with Saudi Arabia or the energy transition when it was necessary to take the national context into account. In order to carry out the discovery or verification, the following databases were used: Scopus, Web of Science, IEEE Xplore, ScienceDirect and Google Scholar. Where appropriate, backward and forward citation checks were performed so as to clarify the terminology and to locate studies that were technically relevant. The analytical core consisted only of English-language peer-reviewed journal articles and conference papers that were directly relevant to digital twins, smart-grid enabling technologies, the combination of renewable grids, cyber-physical security or the Saudi power transition.

The evidence base of the review excluded any sources published outside the period 2020 to 2025, any non-technical promotional material, duplicate entries, papers in which 'digital twin' was used only as a label for offline simulation, and studies in which the energy aspect was only incidental. Thirty of the key publications were selected for in-depth synthesis. As the objective was to produce a concentrated and integrated evidence set rather than to present a complete list of all the publications, the total number of records obtained from the database as a whole is not provided. This approach avoids giving the impression of artificial precision while at the same time allowing for a reproducible rationale: in order to be included, a paper had to satisfy all of the following conditions—relevance, being peer-reviewed, having been published within the allowed date range, having a identifiable DOI, showing methodological clarity, and making a contribution to at least one of the research questions.

3.2 Analytical coding and quality appraisal

The six analytical dimensions employed in the coding process were twin maturity and architecture; data acquisition and interoperability; prediction and optimization; the assimilation of renewable and distributed resources; cyber-resilience and validation; and relevance to Saudi conditions. In the second stage of coding, the reported value was split into reliability, efficiency, sustainability, flexibility, maintainability, and decision quality. Care was taken during the synthesis phase to differentiate between actual outcomes and those which were proposed. For example, evidence gathered in a laboratory or from a demonstrator was seen as proof of feasibility within a specific context and was not treated as evidence that the same level of performance would be obtained across the entire Saudi national grid.

The focus of the assessment was on traceability, not merely on the journal's reputation. Whenever possible, studies were selected because they specified both the physical system and the virtual model, explained how the data was exchanged, reported the conditions under which validation or testing occurred, disclosed the modelling assumptions, and linked the results to an operational decision. Review articles were employed in order to identify recurring architectures and research gaps, while empirical papers were used to verify whether the stated functions had in fact been implemented. Papers that were specific to Saudi Arabia were used for the purpose of establishing the requirements for grid transition rather than for suggesting that digital-twin deployments already exist on a national scale. The final framework was obtained by comparing the recurring functional requirements with the operating needs of Saudi Arabia and then organising them into layers which included explicit interfaces, controls, and evaluation criteria.

4. DIGITAL-TWIN FOUNDATIONS FOR SMART-GRID MANAGEMENT

A digital twin should be considered as a relationship that involves a physical system, a virtual representation, data exchange, models, and services and not merely as a three-dimensional model. The key features highlighted in the relevant literature are the bidirectional connection and the synchronized state. In the case of power systems, this difference is important from an operational point of view. Although a digital model can be used for planning and a digital shadow can receive measurements, a fully developed twin also makes use of synchronized

information in order to forecast conditions, to evaluate the impact of interventions, and, where appropriate, to send decisions back to the physical system. The boundary indicating the level of maturity thus lies in the capacity to make decisions and in the carrying out of feedback, not in the degree of visual detail.

Grid twins also require more than just one type of model. Models derived from physics cover areas such as power flow, dynamics, thermal effects, and degradation, and these reflect the known behaviour of the system, while data-driven models can detect any remaining patterns, forecast demand or the output from renewable energy sources, identify anomalies, and approximate expensive simulations. Hybrid approaches are generally the best option since they retain the physical constraints and at the same time make use of real-time data. A predictor that works well but violates network limits cannot be regarded as true operational intelligence. Conversely, a model that is physically sound but cannot update quickly enough for the control horizon in question has no operational value. The twin's design should therefore match the degree of model accuracy to the decision-making time lag: the timing and verification needed for protection-and-support functions are different from those required for long-term maintenance planning.

The literature also indicates that digital twins should be seen as a set of federated services rather than as one single, integrated national model. Distribution twins, renewable-plant twins, substation twins, storage twins, and microgrid twins may operate at different temporal and spatial resolutions yet still share some state variables and constraints. This modular method reduces the computing load and ensures that ownership boundaries are kept. It also makes governance more straightforward. The main architectural question therefore becomes one of deciding which states must be shared, at what rate, with what level of confidence, and under what control. A federated system of this kind is suitable for a grid that is undergoing change since new assets can be added without the need to rebuild the entire model.

5. SAUDI POWER-INFRASTRUCTURE CONTEXT

The Saudi power infrastructure must meet rapidly increasing demand, take into account its vast geographical area, cope with harsh environmental conditions, pursue major objectives in the field of renewable energy development, and have the background of a centrally managed electricity system. The national transition studies indicate that the policy emphasis is on increasing the proportion of renewable energy, improving energy efficiency, and reducing carbon intensity. These aims go beyond merely adding more generation capacity; they change the way the network functions. As solar and wind power depend on weather conditions, inverter-based resources contribute in a different way to system inertia, energy storage involves making decisions regarding dispatch over time, and distributed resources result in new requirements in terms of visibility at lower voltage levels. An analysis of frequency stability on the Saudi grid reveals that a high level of renewable energy integration calls for a thorough operational evaluation rather than simply replacing one type of generation with another.

The Kingdom also has the opportunity to develop its digital infrastructure. Research into Saudi smart-grid communications indicates that 5G, wireless sensor networks, edge and fog computing, and machine-to-machine security are relevant. These capabilities can provide the data routes needed for digital twins, but the network architecture must be designed with the requirements of critical infrastructure in mind. The high density of sensors results in both greater observability and a larger attack surface. Even though edge processing can reduce latency and bandwidth usage, the distributed nature of computation makes configuration management and trust more difficult. The framework should therefore treat communications, identity, time synchronisation, data quality, and cyber monitoring as first-class grid assets rather than as supporting information-technology services.

The climate and the geographical conditions also have an impact on the design problem, as high temperatures, dust, coastal salinity, and the great distances over which transmission occurs can all lead to equipment degradation, affect the performance of photovoltaic systems, influence the reliability of sensors, and impact the logistics of maintenance. For this reason, a digital twin for

Saudi Arabia should become familiar with the local failure patterns and the way these are related to the environment rather than relying on generally applicable degradation models that have not been calibrated. The same principle should apply in the case of sustainability; a national digital-twin programme should not be assessed merely on the basis of how correct the model is, but should also be linked to outcomes such as reduced curtailment, lower losses, deferred replacement of assets, less maintenance travel, an improved ability to host renewable energy, greater resilience in the face of disturbances, and transparent lifecycle decisions.

An other important contextual element is organizational scalability. The national power infrastructure involves operators, generators, transmission and distribution operations, regulators, technology vendors, and the major energy consumers. If a digital twin attains technical integration but fails to make clear the responsibilities concerning data ownership, model approval, incident response, and control authority, this could result in a higher level of systemic risk. It is therefore necessary for the Saudi deployment to see both technical interoperability and organizational interoperability develop at the same time. The management framework proposed later is based on this dual requirement.

6. EVIDENCE SYNTHESIS: MANAGEMENT APPLICATIONS

6.1 Renewable forecasting and flexibility

The main advantage of a grid digital twin is that it enables forward-looking decisions about operations by taking the current state of the network as a basis. When electric-grid and renewable-energy digital twins are examined, forecasting, scenario simulation, and optimization are always found to be essential functions. For example, when solar and wind power are combined, the twin can integrate weather forecasts, data from the plants, the condition of the inverters, historical performance records, and the network constraints so as to not only estimate the expected output but also to evaluate the operational impact of uncertainty. Management's objective is therefore not to separate out the task of predicting generation; instead it is to forecast possible system states and to secure flexibility in advance in order that forecast errors may not turn into a reliability problem.

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262 Research into microgrids has involved testing this method on a smaller scale. In order to
263 schedule the resources of a microgrid when there are stochastic demand, supply, and price
264 conditions, deep reinforcement learning has been used, while digital-twin prototypes connect
265 real-time data to forecasting, optimisation, and self-healing functions. Demand-side hybrid twins
266 are also capable of giving recommendations that coordinate consumers' assets with the grid's
267 objectives. Yet the studies do not specify a single best algorithm for use in Saudi Arabia; rather,
268 they show that a twin can provide a controlled environment in which forecasting and dispatch
269 policies can be trained, tested, monitored, and revised on the basis of current state information.

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271 6.2 Asset health and predictive maintenance

272 Maintenance is a high-value application since digital twins are able to combine information
273 regarding operational loading, environmental exposure, inspection history, alarms, and
274 degradation models in order to produce dynamic estimates of asset health. In the case of
275 transformers, cables, switchgear, power electronics, and renewable energy assets, the main
276 change in management strategy is a shift from interventions based on the calendar to those that
277 are risk-informed. The digital twin can assess how changes in operating conditions affect the
278 remaining useful life, detect any departures from expected behaviour, and determine whether
279 delaying maintenance or redistributing the load alters the level of system risk.

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281 Predictive maintenance can only be regarded as reliable if the health model has been calibrated
282 and failure uncertainty is clearly stated; false confidence may prove to be expensive in the case
283 of critical infrastructure. Because of this, the existing literature advocates a multi-layered
284 evidence approach in which the raw sensor quality, the obtained condition indicators, the model
285 confidence, the predicted degradation, and the maintenance recommendation all need to be
286 traceable. Research in the field of big data and information management also indicates that data
287 cleansing and integration are necessary prerequisites if analytics are to achieve reliable
288 improvements in sustainability. In the case of Saudi Arabia, environmental elements such as

289 ambient temperature and dust exposure should be included in the asset-specific baselines so that
290 abnormal behaviour can be distinguished from expected climatic effects.

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292 6.3 Distribution visibility, microgrids and coordinated control

293 Distribution networks are a key frontier because distributed generation, storage, flexible demand,
294 and electric vehicles increase the number of active devices below the transmission level. Digital-
295 twin studies of distribution grids emphasize instant monitoring, condition assessment, load
296 forecasting, and layered architectures. A real-world demonstrator further shows that imperfect
297 measurement and network-model data materially influence twin outputs, strengthening the need
298 for uncertainty-aware system estimation. In Saudi Arabia, this suggests that distribution-twin
299 programs should begin where measurement coverage and operational use cases are sufficiently
300 mature, rather than assuming a national model can compensate for weak field data.

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302 Federated microgrid twins can become building blocks for wider coordination. They can
303 exchange feasible operating envelopes, flexibility bids, reserve availability, or security status
304 without exposing every internal device variable. Such abstraction is important for scale and
305 privacy. It also enables local optimization to coexist with system-level constraints. Table 1
306 summarizes these applications. Operationally, local twins can manage fast device-level
307 decisions, regional twins coordinate network limits, and a higher-level orchestration service
308 evaluates cross-area impacts. This architecture is more resilient than a single centralized
309 optimization engine and is compatible with edge-computing trends in smart grids.

310 **Table 1.** Evidence synthesis of digital-twin management applications.

Management domain	Digital-twin role	Potential Saudi infrastructure value	Critical assurance requirement
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Management domain	Digital-twin role	Potential Saudi infrastructure value	Critical assurance requirement
Renewable forecasting and flexibility	Synchronize weather, plant telemetry, network state and flexible resources; test dispatch alternatives before execution.	Higher renewable hosting, lower curtailment, improved reserve preparation.	Forecast uncertainty, model drift, feasible-action checks [14,16,25,26].
Asset health and maintenance	Fuse loading, environmental exposure, alarms, inspections and degradation models.	Risk-informed maintenance, asset-life extension, reduced avoidable outages.	Sensor calibration, failure-data scarcity, confidence reporting [4,10].
Distribution visibility	Maintain topology-aware state estimation and feeder-level scenarios.	Voltage quality, congestion visibility, targeted reinforcement.	Incomplete measurements, topology errors, state-estimation uncertainty [11,12,22].
Microgrids and storage	Coordinate DER, storage and flexible demand through local predictive models.	Resilience, self-healing, efficient local dispatch.	Scalability, interoperability, safe local autonomy [13,14,26,27].
Demand-side services	Model end-use behavior and feasible flexibility without exposing all device details.	Peak reduction, demand response, consumer participation.	Privacy, behavioral uncertainty, incentive alignment [19].
Cyber-resilience	Use the twin for anomaly detection, attack simulation and recovery testing.	Reduced cyber-physical risk and faster response.	Trusted identity, segmented control, adversarial robustness [6,9,30].

7. DATA, INTEROPERABILITY, VALIDATION AND CYBERSECURITY

The quality of data forms the underlying limit between a convincing digital representation and a reliable operational twin. The data from the grid include latency, missing values, errors in the time stamps, sensor drift, inconsistencies in the topology, and anomalies caused by cyber attacks. As a result, the twin must have data lineage so that operators can determine the origin, the transformations undergone, the quality status, and the time validity of the variables employed in a decision. Although edge computing can enhance response time and lessen the communication load, and high-capacity wireless infrastructure can increase the extent of sensing, neither of these approaches eliminates the requirement for common semantics and for disciplined configuration management.

Interoperability must be designed at three levels: syntactic interoperability enables systems to exchange data; semantic interoperability makes sure that the variables exchanged have a consistent meaning, along with consistent units, topology references, and asset identity; operational interoperability specifies how the output of one twin can be taken as the input of another system. Research into distributed-energy platforms shows how important it is to have shared information models and a modular architecture. If these layers are missing, large-scale implementation results in a number of isolated vendor solutions rather than a grid-management ecosystem.

It is just as important to carry out validation since the accuracy of the model changes with time. When the system is commissioned, baseline error levels should be determined for state estimation, forecasting, asset health, and the generation of control recommendations. Operational monitoring must then identify any model drift and initiate recalibration. Evidence from the demonstrator indicates that uncertainty in the measurements and in the network models can have a substantial effect on the decisions of the digital twin. The Saudi framework should therefore attach to each automated recommendation a confidence estimate, a validity horizon, and a fallback mode. Control functions of high impact should only be moved from advisory operation

to supervised control after their performance has been proven under a range of seasonal and contingency conditions.

Cybersecurity has to be incorporated into the digital twin's architecture since the bidirectional connectivity can provide routes from the digital services to physical control. Research into smart-grid security identifies threats to confidentiality, integrity, availability, and device trust. More recent studies have specifically regarded digital twins as both a security risk and as a defensive measure for microgrids. Secure twins need segmented networks, devices that have been authenticated, the principle of least privilege for access, signed updates to the model and configuration, protected logs, the ability to detect anomalies, and separate safety constraints. A compromised twin should not be able to turn a corrupt model into unbounded physical action.

8. PROPOSED SAUDI DIGITAL TWIN SMART GRID MANAGEMENT FRAMEWORK

Figure 1 shows the six-layer framework that has been proposed. The first of these is the physical power-infrastructure layer, comprising generation plants, transmission corridors, substations, distribution feeders, renewable assets, storage, flexible loads, microgrids, and the relevant environmental conditions. The second layer is the sensing and edge layer, which gathers synchronized electrical, mechanical, thermal, meteorological, and cyber telemetry and carries out local filtering, event detection, and low-latency analytics. It is these two layers that determine the quality of physical observability; shortcomings in them cannot be corrected just by using more sophisticated artificial intelligence.

Table 2 matches the six layers with their deployment priorities. The data-context layer keeps track of asset identity, network topology, time-series data, event records, maintenance history, versions, metadata, and data-quality indicators; its function is to ensure that the information can be reused in planning, operations, maintenance, and sustainability assessment. The fourth layer is the twin-model layer, which incorporates network models, dynamic simulation, equipment-health models, forecasting models, and reduced-order or data-driven surrogates. The models are

versioned and calibrated using field observations, with uncertainty being carried forward rather than being hidden.

The fifth layer involves decision intelligence, which transforms synchronized states into forecasts, diagnostics, comparisons of different scenarios, estimates of risk, and suggestions for optimization. Renewable forecasting, contingency screening, voltage support, storage dispatch, asset-health prioritization, demand response, and restoration planning can all be carried out at this layer. It is important that this layer separates the act of predicting from the act of authorizing. Thus, an algorithm can recommend a switching or dispatch action without automatically being given the permission to carry it out.

The sixth layer involves orchestration and assurance and includes operational decision-making authorities, cybersecurity controls, validation thresholds, rules that involve a human operator, audit trails, sustainability indicators, and the interfaces between the local, regional, and national twins. It is because of this layer that the framework becomes a management system rather than simply a software stack. In the case of low-risk functions, automated execution may be sufficient; but for actions which have high consequences, the framework can call for independent constraint checks, operator confirmation, or precedence being given to the protection system. Security monitoring should also check that the data and model behaviour are in line with those of the physical network before any control outputs are issued.

The system functions through a continuous loop in which the measurements update the contextual state, the models compare the observed behaviour with the expected one, the decision services predict and assess different options, the governed orchestration approves the suitable actions, and the measurements taken after the action check whether the actual physical response matches what was expected. It is essential to include the verification step since it turns operation into a learning process; if a prediction consistently differs from reality, the twin must not simply carry on silently, but should detect the drift, determine the probable causes, and send the model for recalibration or retirement.

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On a national scale, these layers should be set up as a federation instead of using a single database or a single model. For example, a twin for a solar plant can be used to optimise the plant's performance, one for a substation can be used to assess the condition of the equipment, and one for the distribution network can coordinate voltage and flexibility. Each of them makes available through controlled interfaces only the states and constraints that it has selected. Regional coordination services then look at the interactions, while the system-level functions continue to have visibility of the security limits and the balancing requirements. This kind of architecture allows for a step-by-step deployment and prevents every local innovation from having to depend on a single central platform.

408 **Table 2.** Six-layer management framework and Saudi deployment priorities.

Layer	Core content	Evaluation focus	Deployment priority
1. Physical power infrastructure	Generation, transmission, substations, feeders, DER, storage, microgrids and environmental exposure.	Asset availability; renewable hosting; operating-limit compliance.	Select bounded use cases where physical measurements and decision ownership are clear.
2. Sensing and edge	Time-synchronized electrical, thermal, mechanical, weather and cyber telemetry with local analytics.	Latency; completeness; sensor health; time-sync quality.	Engineer harsh-environment reliability and secure field-device identity.
3. Interoperable data and context	Topology, asset identity, time series, maintenance history, metadata, lineage and quality flags.	Data-quality score; semantic consistency; traceability.	Adopt common identifiers, controlled schemas and portable interfaces.

Layer	Core content	Evaluation focus	Deployment priority
4. Twin models	Power-flow, dynamic, degradation, forecasting and hybrid surrogate models with uncertainty.	Validation error; drift; validity horizon; computational latency.	Calibrate under Saudi climatic and renewable operating conditions.
5. Decision intelligence	Forecasts, diagnostics, contingencies, optimization, risk estimates and maintenance priorities.	Forecast error; feasible-action rate; decision lead time.	Keep prediction separate from execution authority until validated.
6. Governed orchestration	Decision rights, cyber assurance, audit, human oversight, fallback modes and sustainability accounting.	Audit completeness; incident detection; actions inside approved confidence.	Federate proven twins gradually across local, regional and system levels.

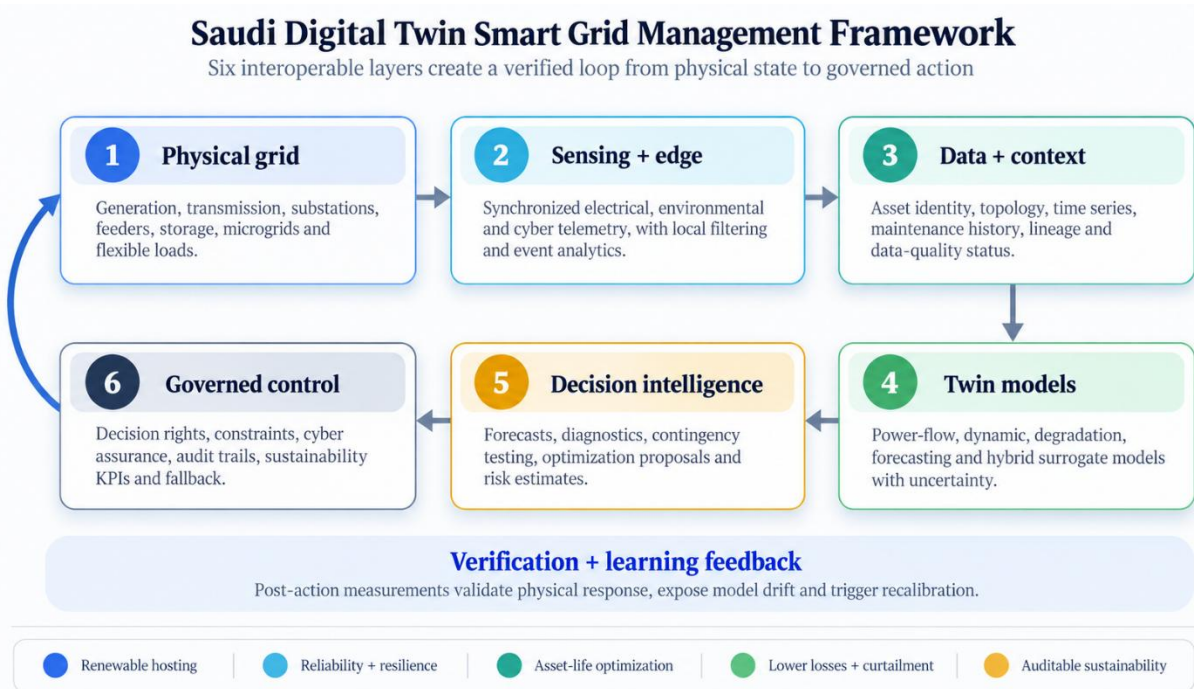


Figure 1. Saudi Digital Twin Smart Grid Management Framework

9. DEPLOYMENT ROADMAP AND PERFORMANCE EVALUATION

Figure 2 illustrates a rollout involving four stages of maturity. In the initial stage, bounded observational twins are established for assets or feeders in cases where there is clear data ownership and operational problems that can be identified and dealt with. In the second stage, validated forecasting, condition assessment, and scenario testing are incorporated, yet advisory decision-making is still maintained. In the third stage, supervised closed-loop actions are introduced for certain low-risk functions, there being independent constraints and fallback procedures to provide support. In the fourth stage, the twins that have been proven are federated across various domains so that the renewable energy plants, the storage systems, the substations, the distribution areas and the microgrids share their standard operational states and flexibility information.

Until widespread automation occurs, utilities should carry out red-team exercises, conduct drills involving model failure, and perform simulations of data loss so that the operators can check the fallback procedures, the hierarchy of protection, the resilience of communication, and the responsibilities relating to recovery in the event that a number of interconnected digital and physical assets are affected by a combination of disturbances.

Assessment of performance should be based on a well-balanced set of metrics rather than on a single model-accuracy score. The technical indicators are state-estimation error, forecast error, model latency, data completeness, synchronization quality, and control feasibility. The operational indicators comprise outage duration, restoration time, renewable curtailment, losses, maintenance deferrals, asset availability, reserve utilization, and compliance with voltage or frequency standards. The sustainability indicators are avoided emissions, improved renewable hosting capacity, reduced maintenance travel, asset-life extension, and energy-efficiency gains. The governance indicators include audit completeness, detection of cybersecurity incidents, model-validation status, access-control violations, and the percentage of automated actions that operate within the approved confidence thresholds. These measures connect the digital performance to the real-world outcomes of the infrastructure.

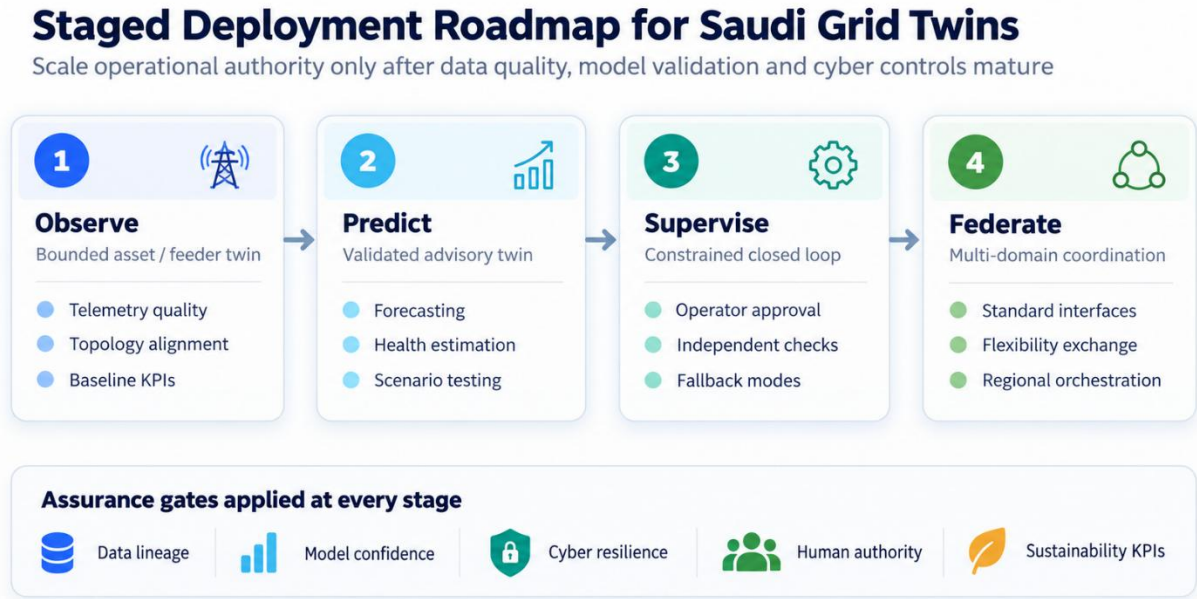


Figure 2. Staged deployment roadmap from bounded observational twins

10. DISCUSSION: RESEARCH GAPS AND PRIORITIES

The review points out four gaps which are especially relevant for the deployment in Saudi Arabia. The first of these is that there is not enough evidence regarding the performance of digital twins in desert environmental conditions; models need to be locally calibrated in order to address asset degradation, sensor behaviour, photovoltaic soiling, thermal limitations, and

communication reliability. Secondly, a number of studies show only individual elements of a twin rather than the entire assurance chain running from field measurement to authorized control; research should thus examine data quality, model uncertainty, cyber integrity, decision latency, and physical response all within the same experiment.

Third, interoperability is still mainly an organisational issue rather than one that is entirely technical. Although standards can specify messages and models, the various utilities still need to have rules concerning asset identity, model ownership, vendor portability, version control, liability, and access across domains. Saudi research programmes could make use of common reference architectures and shared test datasets so that competing solutions can be assessed under similar conditions. Fourth, sustainability claims need to be supported by more rigorous causal measurements. A twin might lead to an improvement in forecasting accuracy without in any way reducing emissions or costs if operational incentives, reserve rules, or network constraints stop any action from being taken. Future studies should connect the outputs of twins to actual changes in curtailment, losses, maintenance, resilience, or the use of resources over a component's lifecycle.

Another important focus is the safe integration of artificial intelligence. Latest reviews indicate a rapid progression towards machine learning, federated methods, and ever more autonomous energy intelligence. However, when it comes to deploying systems on the critical grid, physical limitations must be maintained, explanations appropriate to each decision must be provided, reproducible validation should be carried out, and safe fallback options must be available. Research should involve hybrid models that combine network equations with learned residual behaviour, as well as federated learning which enables local twins to enhance the shared models without centralising sensitive operational data. The relevant question is not whether artificial intelligence can make accurate predictions, but whether its outputs remain trustworthy when there are changes in the topology, during extreme weather, in the case of new faults, in the face of adversarial input, and under distribution shift.

11. MANAGERIAL AND POLICY IMPLICATIONS

For those in charge of infrastructure, the key point is to treat digital twins as long-lasting operational assets. When preparing business cases, one should start by addressing decisions that are costly, uncertain, or hard to observe and then determine the kind of data and modelling

capability needed to improve them. When carrying out procurement, it should require data portability, interface documentation, traceability of model versions, cyber controls, and measurable acceptance criteria. Vendor demonstrations must not take the place of validation based on representative Saudi conditions.

Policy makers and regulatory authorities can speed up achievement of large scale by promoting common standards for interoperability, meeting cyber-assurance requirements, and establishing controlled mechanisms for data sharing. A national test environment would enable utilities, researchers and technology providers to assess twins against standard network scenarios without having to expose live critical infrastructure. Similarly, workforce development is important. Power engineers require better capabilities in data and model governance, while data scientists need a deeper understanding of operational protection, stability and safety constraints. Interdisciplinary teams are needed since a digital twin will fail if either the physical model or the digital operating environment is not properly understood.

12. LIMITATIONS

The review deliberately focuses on peer-reviewed evidence obtained between 2020 and 2025 and on thirty key publications which have verified DOI entries. It does not aim to provide a complete account of every digital-twin study or each instance of proprietary utility deployment. Since there is currently a lack of large-scale evidence from Saudi Arabia, the framework suggested here involves a synthesis that must undergo staged field testing. Hence, any international or laboratory-reported benefits should be regarded as hypotheses that can be transferred, not as assured results for the nation.

13. CONCLUSION

Digital twins can play a significant role as a means of managing sustainable development of Saudi Arabia's power infrastructure, but their value is derived from careful cyber-physical synchronisation rather than from mere visual replication. The relevant literature shows a sequence of stages moving from observation through to forecasting, scenario testing, supervised control, and finally to federated coordination between different parts of the grid. This kind of progression is applicable to Saudi Arabia in the areas of renewable energy integration,

distribution visibility, predictive maintenance, microgrid management, resilience, and lifecycle sustainability.

The six-layer framework that has been proposed connects physical infrastructure with sensing and edge intelligence, interoperable data, calibrated models, decision services, and governed orchestration. The main idea behind its design is that each digital recommendation must be traceable to the quality of the data, the confidence level of the model, the operational authority involved, and to a measurable physical result. On a national scale, achievement should be obtained by federating validated twins rather than by trying to build one universal model before local value has been demonstrated.

A program that is credible ought therefore to focus on definite use cases, common semantics, validation based on the actual conditions in Saudi Arabia, secure interfaces, and clear performance metrics. Since renewable energy penetration and grid complexity are increasing, the most significant contribution of digital twins will be their ability to convert scattered measurements and models into a continuously verified decision-making process. If this process is combined with cyber assurance, institutional accountability, and sustainability measurement, it can help to create an electricity system in Saudi Arabia that is more reliable, more flexible, and more resource-efficient.

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