

Improving the Resilience of Saudi Smart Energy Grids through Distribution Network Planning, Testing and Asset Management

Salim Ullah^{1*} 

¹Mechanical Engineering, Open University of Sri Lanka: Colombo, Western Province, LK

*Corresponding Author

Salim Ullah

Mechanical Engineering,
Open University of Sri
Lanka: Colombo, Western
Province, LK

Article History

Received: 19.08.2026

Accepted: 13.10.2026

Published: 14.10.2026

Abstract: Saudi Arabia is aiming to develop an electricity system that is more reliant on renewables, more digital, and more distributed, and as a result the importance of having a resilient distribution grid is growing. This study looks at how distribution network planning, testing and asset management can be combined in order to minimise service interruptions, manage lifecycle risks and deal with variable renewable generation, storage and flexible demand. The research carried out between 2020 and 2025 is organised around four closely related functions: risk-informed planning, verification and testing, condition-based asset management, and adaptive operation. It has been found that resilience cannot be achieved through the use of a single technology; rather, it arises as a result of coordinated decisions regarding topology, distributed energy resources, storage, protection, automation, equipment health, maintenance and restoration. Studies specific to Saudi Arabia show that expanding renewable energy capacity can improve adequacy, while probabilistic planning of storage can reduce losses and delay the need for network reinforcement; but these advantages depend on reliable models of uncertainty, protection coordination, the quality of the data and the state of the assets. The review suggests an integrated resilience lifecycle in which the assumptions made during planning are checked by means of studies and field tests, operating events update the asset health and the probabilities of failure, and decisions relating to maintenance and investment are then fed back into future network plans. Special attention is paid to the effects of extreme heat, dust, the intermittency of renewable energy, cybersecurity issues and the ageing of key transformer assets. The paper ends with a research programme that focuses on data from Saudi distribution systems, climate-conditioned failure models, hardware-in-the-loop validation, interoperable asset-health indices and the economic valuation of resilience. The framework thus provides utilities with a practical basis for linking their investments in resilience to their reliability, sustainability and Vision 2030 goals.

Keywords: Distribution Grid Resilience; Distribution Network Planning; Asset Management; Condition-Based Maintenance; Renewable Energy Integration.

Copyright © 2026 The Author(s): This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY-NC 4.0) which permits unrestricted use, distribution, and reproduction in any medium for non-commercial use provided the original author and source are credited.

1. INTRODUCTION

Electricity distribution networks are now acting as the central point of the energy transition. The increased use of solar power, battery storage, electric vehicles, smart loads and advanced metering

brings variability and the need for control closer to the end users, and digital protection together with communication open up new possibilities for automation. A resilient distribution network should not merely avoid regular outages; it also has to

Citation: Ullah, S. (2026). Improving the Resilience of Saudi Smart Energy Grids through Distribution Network Planning, Testing and Asset Management. *Glob Acad J Econ Buss*, 8(5), 1899-1910. <https://doi.org/10.36348/gajeb.2026.v08i05.074>

anticipate uncertain stresses, absorb disturbances, keep priority supply running, restore service quickly and draw lessons from incidents. Because of this, recent work on resilience combines planning, operation and restoration into a single risk framework rather than considering reliability as just a historical figure based on interruptions [1–3].

The fact that the Saudi situation makes this integration especially important is clear. The expansion of renewable energy, large-scale urban development and the growing digital infrastructure are all leading to changes in power flows and the operational needs throughout the Kingdom. Research carried out in Saudi Arabia indicates that renewable resources can enhance generation adequacy, although it also stresses the importance of carrying out regional reliability analyses, providing storage, ensuring flexibility and improving the way uncertainty is handled [4–7]. Distribution networks have to be able to handle high levels of photovoltaic output during the day, swiftly changing demand, long feeder distances in certain areas, peak loads caused by heat and environmental stresses which speed up the ageing of insulation and equipment. Meanwhile, digitalization raises the dependence on communication, data integrity and cyber-secure control [8].

The three functions are usually examined on their own. Distribution planning is responsible for deciding the network topology, the need for reinforcement, automation, the use of distributed energy resources and storage. Testing checks that the equipment, the protection systems, the controls and the models behave as they should in both normal and abnormal conditions. Asset management takes the data from inspections and assessments and turns it into decisions regarding maintenance, refurbishment and replacement. When the functions are kept separate, this can lead to overlooked weaknesses: the planning model might assume that switching or storage facilities are available when in fact they have not been tested under stressed conditions; the protection settings might become unsuitable after inverter-based resources have been added; and the asset plan might focus on the age of the equipment rather than on the consequences of a failure in the reconfigured network.

The review looks at how planning, testing and asset management can be combined to form a lifecycle for Saudi smart distribution grids that is oriented towards resilience. It begins by arranging the latest evidence into a causal chain which connects hazards, network states, verification, asset condition, intervention and resilience outcomes. It then sets resilience apart from traditional adequacy and reliability while also showing the areas in which their

metrics coincide. After that, it converts findings from abroad into implementation priorities that are specific to Saudi conditions, without assuming that the results from other climates, regulatory environments or network structures can be directly applied. Finally, it points out existing research gaps concerning equipment failure under climate conditions, field validation, cyber-physical testing, the interoperability of asset health data and the valuation of avoided disruption.

2. Aim, Objectives and Review Questions

This review seeks to establish an integrated, evidence-based framework for enhancing the resilience of Saudi smart energy grids by means of coordinated planning of the distribution network and testing, as well as the management of assets. The analysis is guided by four objectives. The first of these is to identify which planning measures have the greatest effect in improving a distribution network's ability to cope with uncertainty and high-impact disruptions. The second objective is to assess the extent to which testing, commissioning and model validation lessen the gap between the resilience that is designed into the system and that which is actually achieved in the field. The third objective is to look at the way in which condition monitoring, health indices and the lifecycle decisions regarding critical equipment affect the overall resilience of the system. The fourth objective is to combine the results of the study into a lifecycle approach that is tailored to Saudi conditions, linking investment, verification, operation, maintenance and learning.

The review looks at four questions: Which of the distribution-planning decisions are best supported by evidence of resilience benefits? How should utilities test the protection, control, storage and restoration functions before using them during disruptive events? In what way can information on asset health and the remaining lives of assets be included in planning and restoration priorities? What data, models and governance capabilities are still lacking in order to establish a defensible Saudi resilience strategy?

3. REVIEW METHODOLOGY

A critical review based on a structured approach was employed to summarize the peer-reviewed literature that was published between 2020 and 2025. The searches were carried out using combinations of the following terms: distribution network, smart grid, resilience, reliability, planning, battery energy storage, distributed generation, testing, commissioning, protection, condition monitoring, transformer, health index, asset management, Saudi Arabia and renewable integration. Three of the provided papers were used as references both in terms of methodology and

subject matter: one of these looks at the reliability of the Saudi grid in the context of renewable energy expansion, another one involves the development of probabilistic planning for storage in smart distribution networks, and the third examines secure decentralised energy systems within the Saudi context [4–6].

To be included, a study had to have been published between 2020 and 2025, have to be directly relevant to distribution-grid resilience or have to form part of the planning–testing–asset chain, and also had to include enough methodological detail to allow the decision problem, the intervention and the outcome to be identified. Studies that concerned themselves only with the performance of generation technology and not with the network or resilience aspects were excluded.

The synthesis was thematic and not meta-analytic since there are considerable differences among the outcome measures in the existing literature. While some studies give figures for loss of load expectation or expected energy not supplied, others measure restoration, cost, regret, voltage performance, component failure probability or health index. It would therefore be wrong to carry out a direct numerical pooling. Instead, the evidence was organised into five themes: resilience concepts and metrics; planning under uncertainty; testing and operational verification; condition-based asset management; and Saudi implementation. More interpretive weight was attached to those studies which explicitly model uncertainty, link component behaviour to system outcomes, validate their findings on recognised test systems or on real networks, and discuss operational constraints.

Table 1: Review scope and evidence-selection logic

Element	Included evidence	Rationale
Period	2020–2025 peer-reviewed studies	Maintains the requested contemporary evidence window.
Core domains	Distribution resilience, planning, testing, protection, storage, condition monitoring and asset management	Captures the full planning–testing–asset chain.
Saudi evidence	Renewable reliability, smart distribution planning and secure decentralized-grid studies	Supports regional interpretation without assuming universal transferability.
Exclusions	Technology-only studies without network relevance; unverifiable or retracted material	Protects scope and reference integrity.
Synthesis	Thematic critical review rather than pooled meta-analysis	Metrics and network contexts are heterogeneous.

4. Resilience as a Distribution-System Planning Objective

Reliability and resilience may overlap but are not equivalent. When it comes to reliability, the focus is generally on credible component outages and on recurring service interruptions; resilience, on the other hand, places more emphasis on high-impact events, correlated failures, degraded operating states, and the speed and quality with which recovery takes place. Modern evaluations regard resilience as a time-dependent property consisting of preparation, absorption, adaptation and restoration [1–3].

Resilience planning therefore goes beyond simple traditional reinforcement and treats topology, sectionalizing, automation, microgrids, distributed generation, storage, mobile resources, hardening and restoration logistics as part of a portfolio. Stochastic investment studies have shown that automation, hardening and distributed energy resources can be co-optimized in order to balance the gains in resilience against cost [9]. Likewise, two-stage and robust formulations show the advantage of taking into account uncertain hazard intensity, line damage and load variation during the planning process rather than after the network has been designed [10,11]. Extreme temperatures increase peak demand while

at the same time speeding up the ageing of equipment; dust and soiling reduce the output of photovoltaic systems while increasing the need for maintenance; and a disturbance may take place when the state of charge of the storage or the availability of renewables is adverse.

It is particularly important because it connects normal operation with the response to disturbances. Reviews of storage technologies and optimization indicate that the performance of BESS is influenced by its size, where it is sited, the operating constraints applicable and the objective adopted for planning [12, 13]. Studies at the distribution level show a number of benefits—such as reduced losses, voltage support, energy arbitrage, the ability to accommodate renewables and the deferral of reinforcement—when storage is properly sited and controlled [5-15]. Work focusing on resilience also includes support for islanding, the supply of critical loads and increased restoration flexibility. A battery that has been optimized solely for daily energy arbitrage can be emptied out if a disruption takes place. Planning therefore needs to leave aside some operational headroom, take account of degradation and consider the probability and length of outage scenarios.

Microgrids and local energy communities are able to ensure a supply of electricity to certain loads and decrease their reliance on a single upper-level supply route [16, 17]. However, the advantage of islanding is only realized when protection, synchronization, control and communication functions have been verified. Islands dominated by inverters may have smaller fault currents and different frequency characteristics than conventional systems.

For Saudi planners the key point is that investments in resilience must be tailored to each

location. The fact that the country has set national targets for renewable energy does not mean that the impact will be the same everywhere. Coastal, urban, industrial and remote networks all have different load patterns, different levels of environmental exposure and different constraints when it comes to restoration. Analyses of Saudi Arabia's renewable potential and adequacy show the importance of using site and seasonal data [4]. The planning process should therefore take into account feeder-level hosting capacity, probabilistic demand and renewable scenarios, climate exposure, asset criticality and restoration accessibility.

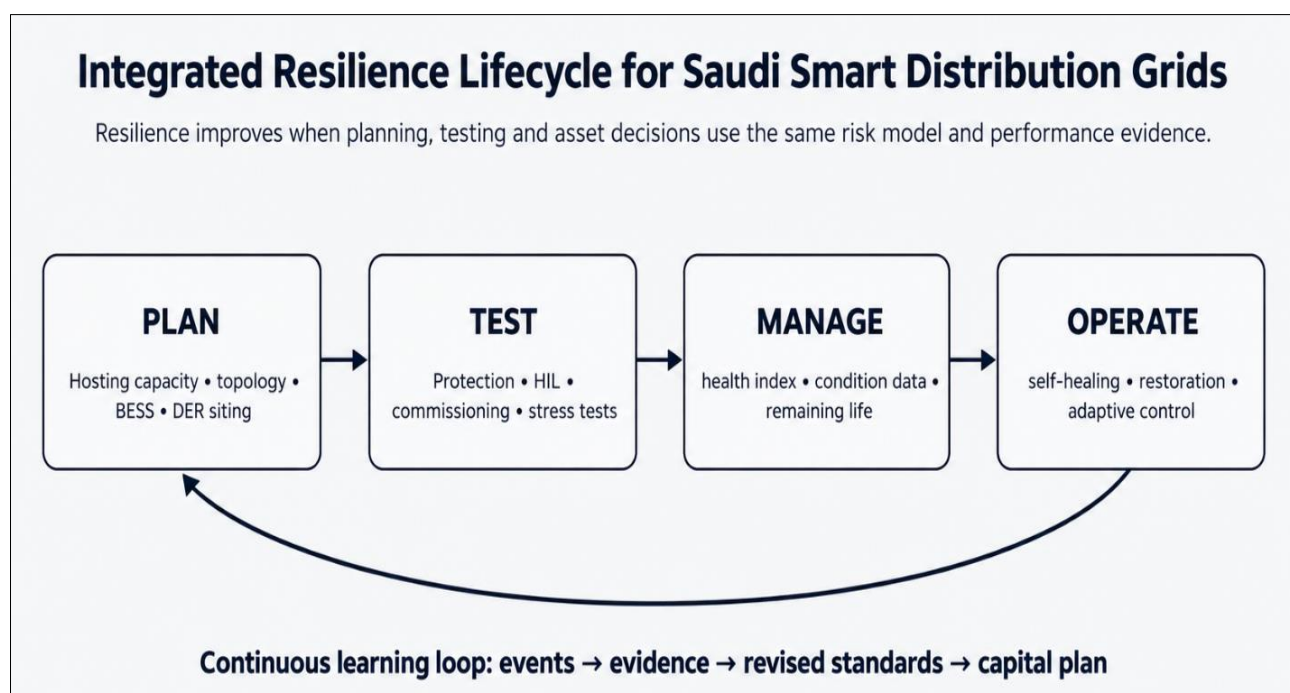


Figure 1: Integrated resilience lifecycle linking planning, testing, asset management and operation

5. Testing and Verification: Converting Designed Resilience into Available Resilience

A resilience plan is of little use if the functions it relies upon cannot be demonstrated; evidence of the continued validity of network models, equipment, settings and coordinated controls is provided by testing as the distribution system develops.

The initial stage involves model validation. When carrying out planning studies, it is necessary to use feeder impedances, the way the load is allocated, the profiles of distributed generation, the characteristics of transformers and protection data. In order to check the models against actual measurements, advanced metering and supervisory data should be employed with regard to voltage, power flow and the behaviour of events. If there are large discrepancies, the data should be corrected before the models are used for hosting capacity, contingency or restoration studies. The credibility of

probabilistic planning is no greater than the quality of the distributions assumed for demand, irradiance, wind, equipment availability and price. Research into energy storage in Saudi Arabia demonstrates the advantage of explicitly taking into account the uncertainties of wind, solar and load rather than reducing them to deterministic averages [5].

The second stage involves protection and control testing. In order to achieve resilience it is necessary to carry out selective isolation, meaning that a fault should cause the smallest possible section to be removed while the other good parts remain powered or are restored by means of alternative routes. Utilities must therefore check their settings in relation to a range of credible network topologies and states involving distributed energy resources, including both the minimum and maximum fault currents, loss of communication, failure of switching devices and the transition to islanded operation. Hardware-in-the-loop and controller-in-the-loop

systems are useful since they reveal the interactions that static studies might overlook, especially in the case of vendor controls which include proprietary logic.

The third stage involves asset and functional testing, with critical components such as transformers, cables, switchgear and batteries needing to undergo tests that show signs of deterioration before failure occurs. According to literature on transformer asset management, dissolved gas analysis, oil quality, partial discharge, thermal monitoring, insulation measurements, frequency response and other diagnostic methods are considered as inputs to the health assessment [18–20]. These factors affect the probability that an asset believed to be available in a restoration plan will in fact function, and they also highlight those components whose failure would warrant the introduction of redundancy or accelerated replacement.

In the end, resilience testing ought to involve exercises, and tabletop exercises for restoration can be used to check switching authority, communication routes, the availability of spares, field access and the process of escalating decisions. For Saudi networks, the scenarios needed should cover high-temperature peaks, dust-caused reductions in renewable energy output, simultaneous equipment derating, communication losses and extended upstream interruptions. The value of these exercises is both organizational and technical in that they show whether the planning assumptions, the asset data and the operating procedures are mutually consistent.

6. Asset Management as a System-Resilience Function

The determination of whether the required network capabilities remain physically available over time is carried out by asset management. Maintenance cannot be based solely on age since assets that are the same age can have very different loading histories, degrees of environmental exposure, and conditions. Modern methods combine inspection, monitoring, diagnostic tests, failure history, and criticality into health indices or probabilistic remaining-life models [18–21].

Reviews indicate that dissolved gas analysis, together with measurements of moisture, acidity, furan indicators, partial discharge, thermal data and electrical tests, can identify various deterioration mechanisms [18, 19]. Health indices combine the heterogeneous measurements into a decision signal, whereas remaining-life models assist in deciding when refurbishment or replacement should take place [20]. The methods should be taken in connection with the consequence to the network. A

transformer that is only moderately degraded and which supplies a hospital, a data centre or a constrained radial area might justify earlier intervention than a transformer in poorer condition but with strong transfer capacity and for which a spare part is readily available.

Risk-based asset management therefore links the probability of failure with the consequences of failure, and these consequences should cover the expected customer interruption, the exposure of critical loads, the restoration time, safety, the environmental impact, the replacement lead time and the loss of network flexibility. This is especially important in the case of smart grids since the value of an asset can vary with the topology; a switch, a battery or a transformer which seems non-critical when the system is operating under normal conditions may become essential during islanding or when a feeder is transferred. It is therefore necessary to recalculate the criticality of assets following major connections of distributed energy resources, network reconfigurations or changes in the restoration strategy.

The maintenance strategy has an impact on resilience as well; time-based maintenance, although simple, may result in excessive maintenance of assets that are in good condition and at the same time fail to identify those that are deteriorating rapidly. Condition-based maintenance focuses on the degradation that is observed; predictive maintenance incorporates statistical or machine-learning forecasts; and risk-based maintenance prioritises the interventions according to the consequences for the system. The most suitable approach for the Saudi utilities is probably a stepped model in which high-criticality assets should be subject to continuous or frequent monitoring together with a clear assessment of their remaining life, medium-criticality assets can have periodic condition testing carried out, and low-criticality assets might stay on their streamlined preventive maintenance routines. This kind of allocation enhances the resilience benefit obtained from limited inspection and maintenance resources.

It is necessary to take the environmental conditions into account when building health models since high ambient temperatures speed up thermal ageing and can lower equipment ratings. Dust, contamination and humidity have an effect on insulators, cooling systems and the performance of photovoltaic cells. Sandstorms can at the same time decrease power generation and increase the exposure of outdoor equipment. Generic health limits which have been established for temperate systems may therefore lead to incorrect classifications of the assets in Saudi Arabia unless the equipment is

calibrated to match the local operating conditions. The existence of this research gap is not due to there being no sensors; it is because the local stresses, the condition of the equipment and the consequences for the network have not been integrated into a coherent decision model.

7. Integrating Planning, Testing and Asset Management

The evidence points to the need for an integrated resilience lifecycle rather than three separate programs. Figure 1 shows the cycle. The planning stage involves defining the network states and capabilities required to reduce disruption. Testing ascertains if those capabilities are technically available. Asset management assesses whether they will stay available throughout the investment period. Operations produce new information regarding loads, failures, control performance and restoration. The information obtained in this way is then used to update future plans.

A practical way of implementing this starts by using a standard risk register at both the feeder and substation levels. Each risk entry must link a hazard to the assets that are vulnerable, to the operational consequences and to the available mitigating measures. For instance, in the case of extreme heat the demand may go up, the transformers may have to be derated and the spare thermal capacity may be reduced. The response in the planning stage could involve feeder transfer capability and the use of battery energy storage systems (BESS); the testing response would check that the transfer settings and battery support function properly when the load is high; the asset response should give priority to the transformers that are under thermal stress and to the cooling systems. The risk is managed in a coherent manner since all the different functions make use of the same scenario and consequence definitions.

The data architecture provides the necessary foundation. As illustrated in Figure 2, there is a progression moving from hazards and uncertainty through to network evidence, analytics, interventions and finally outcomes. The various data sources such as smart meters, SCADA systems, protection records,

power-quality monitors, weather data, transformer diagnostics and maintenance histories should all be connected via stable asset identifiers. If such a linkage is not established, then planners will not be able to determine whether the supposed failure rate coincides with actual field experience, and the asset teams will not be able to assess the impact of a deteriorating component on the restoration process. Hence, data quality controls act as a measure of resilience; just as damaging to the quality of decision-making can be the absence of topology status, inconsistent naming or unverified timestamps as an incorrect electrical parameter.

Decision analytics ought to integrate probabilistic planning with asset health. When developing a feeder reinforcement model it is possible to take into account the failure probability of the existing transformers or switches rather than assuming that all assets are perfectly available. On the other hand, an asset replacement model should include the option value resulting from network automation, transfer capacity or storage. This prevents double spending: a utility might find that a small amount of automation is sufficient to reduce the impact of a transformer failure enough to delay replacement, or that a worsening substation asset makes a planned islanding scheme too risky without redundancy.

Performance governance ensures that the process is closed. In order to monitor resilience, both reliability outcomes and stress-event indicators should be tracked before and after interventions. Appropriate measures are those such as expected energy not supplied, the amount of critical load served, restoration time, the number of customers interrupted, the probability of successful islanding, the availability of key automation, the asset health trajectory, and the time taken to deploy spares. The adequacy studies for renewables in Saudi Arabia currently make use of probabilistic reliability indices such as LOLE and LOEE [4]. Distribution-level resilience dashboards can build on this by including restoration and asset-health metrics. The aim is not to produce a single overall score, but rather to make the trade-offs evident and auditable.

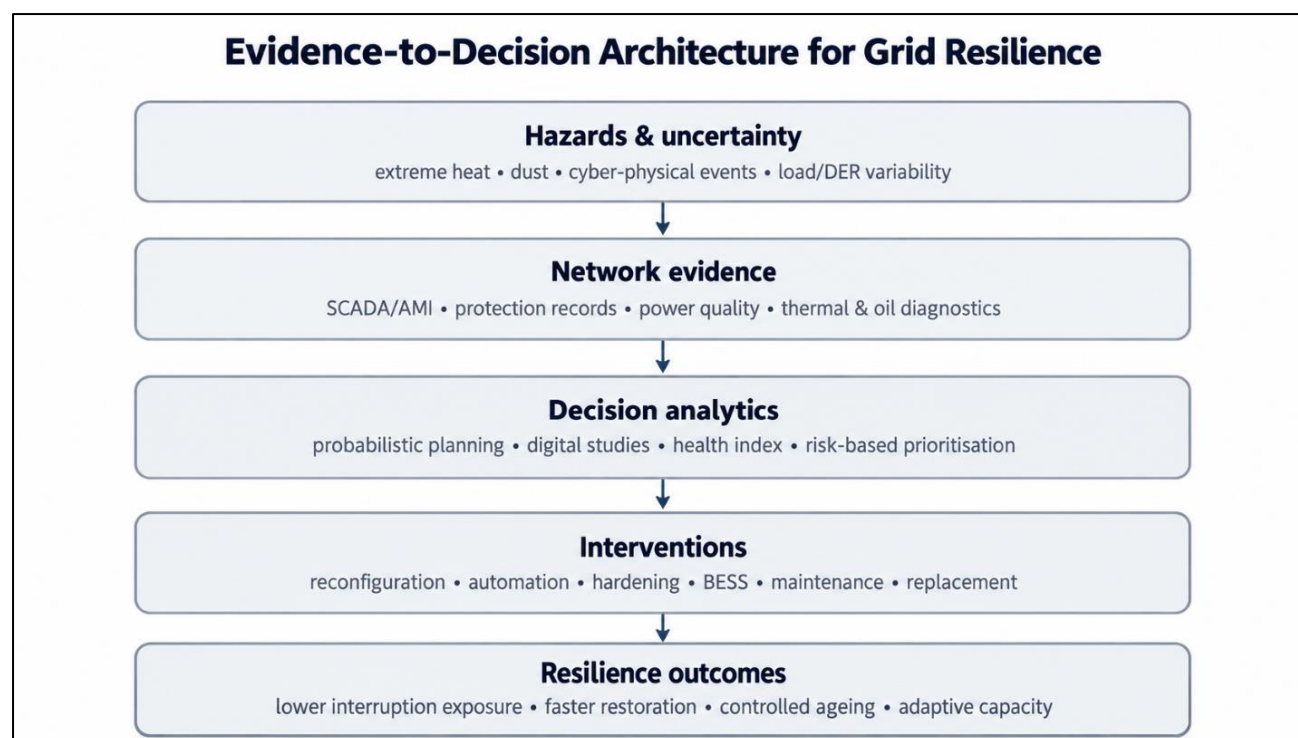


Figure 2: Evidence-to-decision architecture for resilient smart distribution grids

8. Saudi Arabia: Priority Applications and Constraints

The energy transition in Saudi Arabia provides a clear reason for adopting a resilience-focused approach to distribution planning. The country enjoys good solar resources, is expanding its renewable energy projects, and has set ambitious targets for decarbonization, but the physical and operating environment brings with it particular limitations. Because of renewable energy variability, the high demand during summer, the frequent periods of high temperature, dust build-up, the scale of large development projects and the geographically diverse nature of the networks, planning assumptions imported from elsewhere should be adjusted rather than simply copied [4–24].

The main concern should be ensuring that distribution hosting capacity is maintained within resilience constraints. In the case of traditional hosting-capacity analysis, the amount of DER that can be connected without exceeding voltage, thermal or protection limits is determined. A version that takes resilience into account should also examine whether the DER improves or worsens the restoration process. Since photovoltaic generation lacking grid-forming capabilities may offer limited support during an upstream outage, storage or controllable generation might be more valuable in feeders that serve critical loads. Planning must therefore make a distinction between energy contribution and resilience contribution.

The next most important consideration is the placement of storage systems in relation to feeder risk. Research carried out by Saudi authorities on probabilistic BESS planning indicates that optimal sizing and location can lead to a reduction in losses, the deferral of upgrades, and an improvement in operational economics when dealing with uncertain renewable generation and demand [5]. Resilience planning can be incorporated into the objective function by adding provisions for critical-load support, shorter restoration times, and contingency reserves. This is particularly important in the case of remote loads or networks where the logistics of repair contribute to longer outages. The resulting location may be different from the one chosen if arbitrage or loss minimisation alone had been the only objective.

The third priority is concerned with climate-conditioned asset management; the health of transformers, cables and switchgear should be assessed in light of the local thermal and contamination exposure. The thresholds and remaining-life models for important assets should be calibrated using data from the Saudi field. Studies relating to transformer asset management stress that condition monitoring and health indices are of limited value unless the diagnostic evidence is turned into decisions regarding maintenance and replacement [18–20]. The calibration could be greatly improved by the existence of a national or utility-wide anonymised failure database.

The fourth priority is cyber-physical resilience; the introduction of smart-grid communication and automation increases the attack surface and results in dependencies which are absent in passive networks [8-30]. Security measures must be incorporated into restoration testing, including fallback options in the event of lost communication or compromised data. Local, autonomous protection and control can reduce the impact of a wide-area communication failure, while the use of authenticated and time-synchronized data enhances operators' confidence when responding to disturbances.

Lastly, the implementation in Saudi Arabia should take place in phases. It is possible to use high-criticality feeders and substations as pilot schemes for improving resilience, incorporating detailed models, proven automation, storage where it is appropriate, improved monitoring and systematic learning after events. The lessons learned can then be made into standards for broader implementation. Thus, the risk associated with large-scale technology rollouts whose resilience has not been proven under local conditions is reduced.

Table 2: Resilience levers, verification needs and Saudi application priorities

Lever	Resilience mechanism	Verification evidence	Saudi priority
BESS	Critical-load support, peak relief, islanding reserve	State-of-charge policy, dispatch tests, degradation model	High on constrained/critical feeders
Automation & reconfiguration	Fault isolation and service restoration	Protection coordination, switching sequence, communication fallback	High where transfer capacity exists
DER/microgrids	Local supply during upstream interruption	Islanding, grid-forming behavior, black-start and synchronization	Targeted to critical-load clusters
Asset health analytics	Reduces probability of hidden failure during restoration	Condition tests, health index, remaining-life calibration	High for transformers and long-lead assets
Hardening & redundancy	Reduces physical failure and common-mode exposure	Fragility assumptions, inspection and stress tests	Site-specific to climate and consequence

9. CRITICAL DISCUSSION

In the literature that has been reviewed, there are three main findings that are consistent. Firstly, resilience is enhanced when planning specifically takes into account uncertainty and correlated disruptions rather than merely focusing on the optimal performance of normal operations [9–26]. Secondly, distributed flexibility—particularly that provided by storage, reconfiguration and controllable resources—can help to reduce disruption, although its value varies according to location, state of charge, control mode and network constraints [5-27]. Thirdly, the condition of the equipment affects the credibility of any restoration strategy, so asset health must be included as an input to system resilience rather than being treated as a separate maintenance issue [18–21].

There are still important limitations. A great many of the planning papers make use of standard test feeders and simplified hazard scenarios; although they do show the mechanisms involved they do not illustrate the specific benefits for sites in Saudi Arabia. The reliability and resilience metrics also differ, which makes it hard to compare the results. While some of the studies focus on minimizing expected cost, others aim at minimizing expected unserved energy, regret, load restoration, or the health index. A solution which works well with

respect to one objective may shift the risk to another area. For instance, aggressive switching may improve restoration but at the same time increase switching duty, protection complexity and equipment wear. Likewise, frequently using battery reserves in order to enhance resilience can reduce arbitrage revenue and speed up degradation if the cycling policy is not well designed.

The literature also tends to give too little attention to testing. Optimization studies usually assume that the switches function, that communication is available, that the controls converge and that the DER is able to island as it has been modelled. Asset studies tend to end with diagnosis without measuring the effect on the network. A publishable resilience framework has to link these different areas. Planned capability should only be given resilience credit after it has been verified, and the asset health should affect that credit over time. It therefore makes sense to introduce the idea of "available resilience", which is the part of the designed resilience that is demonstrably working given the current state of the assets, the readiness of the controls and the present operating state.

For Saudi Arabia, the idea of resilience is a valuable one from the point of view of governance since the grid is undergoing rapid changes. The

introduction of new renewable energy connections, storage systems, digital substations and smart-city loads can cause changes in network behaviour more quickly than traditional maintenance cycles allow. If the protection settings, the firmware, the communication routes or the condition of the assets change during the course of a year, then an annual planning study is not adequate. Instead, a living resilience model, which is updated using operational and asset data, could enable more defensible investment and maintenance decisions.

There is also the matter of economic evaluation. Although resilience benefits are usually given in terms of reduced unserved energy, the value of the supply varies according to the type of customer and the length of the event. Critical infrastructure, industrial processes and digital services could suffer nonlinear effects as a result of a prolonged interruption. Future analysis by Saudi authorities should therefore include customer damage functions, the priorities for critical services, spare and logistics costs, and the cost of avoiding emergency response. Only in this way can investments in resilience be compared with conventional reinforcement and asset replacement on a lifecycle basis.

10. Research Gaps and Future Directions

From the synthesis there arise five areas of research. The first of these is the development of a dataset on the distribution of resources in Saudi Arabia. Utilities require standardised records that link together information on weather conditions, the topology, the operation of the protection systems, the cause of an interruption, the sequence of restoration, the condition of the assets and the maintenance actions. A dataset of this kind would enable local failure models to be developed and would allow the planning assumptions to be checked against actual events.

The other point concerns the fragility of components under climate conditions. As current resilience studies have shown, failure probability is influenced by both the age of the component and the intensity of the hazard [26]. Saudi Arabia's models should apply this principle to extended exposure to heat, dust and contamination, taking into account any interactions with the component's loading and maintenance history. Fragility curves should be prepared for transformers, overhead lines, cable accessories, switchgear and communication equipment in cases where there is adequate evidence.

The third option is the integrated validation of inverter-rich restoration. Hardware-in-the-loop studies must examine feeder reconfiguration, grid-forming storage, protection mechanisms, and microgrid transitions in the presence of

communication delays and device failures. The aim is to determine the boundary between simulated feasibility and operationally proven capability.

The fourth aspect is interoperable asset health. Although research into the transformer health index has reached a mature stage and now offers useful methods, the utilities still require consistent data models and decision thresholds [18–21]. Future work must involve linking the health states directly to probabilistic network studies so that changes in deterioration affect the contingency probabilities, the restoration options and the timing of investments.

The fifth aspect is resilience economics, which involves assessing the value of avoided interruption, deferred reinforcement, maintenance savings, battery degradation, spare strategy, and restoration resources all within a single lifecycle framework. Robust and stochastic optimization methods already have a solid mathematical basis [9–29]. The following stage is to feed these methods with data on Saudi costs, failures, and customer consequences.

The directions support one another: improved field data lead to better fragility and health models; the better models in turn identify the most important tests; testing shows the limitations of control; and the economic analysis then turns these results into capital priorities. The research programme should thus be based on shared utility datasets and demonstrator feeders rather than on separate technology studies.

11. Practical and Policy Implications

What this means for distribution utilities is that they should set up a joint system covering planning, operations, and asset governance with the aim of improving resilience. When carrying out capital projects, it is necessary to record the disturbance scenarios that they are meant to mitigate, the functions that have to be tested, and the asset-health assumptions upon which the benefits rely. The commissioning process should generate evidence that can be incorporated into planning models, and the reviews following an event should update both the protection studies and the asset risk.

Regulators and policy makers ought to have performance criteria that differentiate between routine reliability and high-impact resilience. Incentives which are based solely on average interruption indices might lead to a lack of investment in those cases where the main benefit is seen during rare and serious events. Yet the financing of resilience measures should continue to be based on evidence. Requiring a scenario to be defined, capabilities to be tested, a lifecycle cost to be

considered and measurable results to be achieved can increase transparency without specifying particular technologies.

In the case of technology procurement, more attention should be paid to interoperability and data ownership. The devices used in the smart grid should provide event and condition data that is time-stamped and presented in a format that allows it to be linked to asset registers and planning models. Cybersecurity requirements must include provisions for updates, authentication, secure fallback procedures and logging. When it comes to storage procurement, the specifications should refer to resilient operating modes and reserve requirements rather than merely stating the energy and power ratings.

Resilience also includes workforce capability, since those engineers who are in charge of planning, protection, automation and asset management need to take part in common scenario exercises and use the same data definitions. Should the responsibilities be spread out during an event, the technical architecture could fail. Training and drills should therefore be regarded as part of the resilience investment and not as administrative overhead.

12. Limitations

The review only includes literature that was published between 2020 and 2025 and thus does not mention earlier foundational studies, even though these had established a number of widely used reliability concepts. Since the studies reviewed involve heterogeneous networks, hazards, objectives and outcome measures, the synthesis has to be presented in a narrative form. It would be wrong to interpret the numerical results from international test systems as direct predictions for Saudi feeders. The paper also focuses on distribution networks and fails to give a complete treatment of transmission-system resilience. Lastly, the publicly available literature contains less Saudi field failure and maintenance data than is needed for carrying out a calibrated asset fragility analysis or for carrying out an economic valuation. These limitations support, rather than undermine, the main recommendation regarding the need for locally validated data and testing.

13. CONCLUSION

Enhancing the resilience of Saudi Arabia's smart energy grids involves more than just increasing the amount of generation, storage or automation. Resilience is achieved when distribution planning, testing and asset management function as a single learning system. Planning must take into account uncertainty, correlated failures, critical loads and restoration options. Testing should confirm that the

protection, communication, storage, islanding and switching functions work when conditions have deteriorated. Asset management should constantly update the probability that key equipment will still be available when the restoration plan calls for it.

The evidence examined shows that storage, the use of distributed resources, network reconfiguration, hardening and automation are all useful as means of enhancing resilience, but no one of these has value everywhere regardless of location and the particular way in which operations are carried out. Expansion of renewable energy in Saudi Arabia can help to improve adequacy, while probabilistic distribution planning can lead to better economics and greater flexibility in the deployment of storage [4,5]. However, these benefits will only become lasting when climate exposure, cyber-physical dependencies and the state of the equipment are taken into account in the decision-making process.

The lifecycle proposed fills the gap between the level of resilience that is designed and that which is actually available. It improves planning models by making use of data from operating events and conditions, verifies the assumed capabilities through testing, and maintains those capabilities over time by means of risk-based decisions regarding assets. For Saudi Arabia, the most valuable actions to take next are to develop local resilience datasets, to create failure models that take account of climate conditions, to carry out hardware-in-the-loop validation, to establish interoperable health indices, and to carry out a lifecycle economic valuation. Taken together, these measures offer a technically sound way of bringing the resilience of the distribution grid into line with renewable integration, service continuity and the long-term goals of Vision 2030.

REFERENCES

1. Bhusal, N., Abdelmalak, M., Kamruzzaman, M., Benidris, M. Power System Resilience: Current Practices, Challenges, and Future Directions. *IEEE Access* 8 (2020) 18064–18086. <https://doi.org/10.1109/ACCESS.2020.2968586>
2. Mahzarnia, M., Moghaddam, M.P., Baboli, P.T., Siano, P. A Review of the Measures to Enhance Power Systems Resilience. *IEEE Systems Journal* 14 (2020) 4059–4070. <https://doi.org/10.1109/JSYST.2020.2965993>
3. Liu, X., Shahidehpour, M., Li, Z., Liu, X., Cao, Y., Bie, Z. Resilient Distribution System Leveraging Distributed Generation and Microgrids: A Review. *IET Energy Systems Integration* 2 (2020) 289–304. <https://doi.org/10.1049/iet-esi.2019.0134>

4. Almutairi, A., Alhamed, Y. Sustainability and Grid Reliability of Renewable Energy Expansion Projects in Saudi Arabia by 2030. *Sustainability* 17 (2025) 4493. <https://doi.org/10.3390/su17104493>
5. Alguhi, A.A., Alotaibi, M.A., Al-Ammar, E.A. Probabilistic Planning for an Energy Storage System Considering the Uncertainties in Smart Distribution Networks. *Sustainability* 16 (2024) 290. <https://doi.org/10.3390/su16010290>
6. Khubrani, M.M., Alam, S. Blockchain-Based Microgrid for Safe and Reliable Power Generation and Distribution: A Case Study of Saudi Arabia. *Energies* 16 (2023) 5963. <https://doi.org/10.3390/en16165963>
7. Almulhim, A.I. Understanding Public Awareness and Attitudes toward Renewable Energy Resources in Saudi Arabia. *Renewable Energy* 192 (2022) 572–582. <https://doi.org/10.1016/j.renene.2022.04.122>
8. Ghiasi, M., Niknam, T., Wang, Z., Mehrandezh, M., Dehghani, M., Ghadimi, N. A Comprehensive Review of Cyber-Attacks and Defense Mechanisms for Improving Security in Smart Grid Energy Systems: Past, Present and Future. *Electric Power Systems Research* 215 (2023) 108975. <https://doi.org/10.1016/j.epsr.2022.108975>
9. Ghosh, P., De, M. A Stochastic Investment Decision Making Method for Distribution System Resilience Enhancement Considering Automation, Hardening and Distributed Energy Resources. *Reliability Engineering & System Safety* 237 (2023) 109395. <https://doi.org/10.1016/j.res.2023.109395>
10. Hou, H., Tang, J., Zhang, Z., Wang, Z., Wei, R., Wang, L., He, H., Wu, X. Resilience Enhancement of Distribution Network under Typhoon Disaster Based on Two-Stage Stochastic Programming. *Applied Energy* 338 (2023) 120892. <https://doi.org/10.1016/j.apenergy.2023.120892>
11. Jannati-Oskuee, M.-R., Gholizadeh-Roshanagh, R., Najafi-Ravadanegh, S. Robust Expansion Planning of Reliable and Resilient Smart Distribution Network Equipped by Storage Devices. *Electric Power Systems Research* 229 (2024) 110081. <https://doi.org/10.1016/j.epsr.2023.110081>
12. Hossain, E., Faruque, H.M.R., Sunny, M.S.H., Mohammad, N., Nawar, N. A Comprehensive Review on Energy Storage Systems: Types, Comparison, Current Scenario, Applications, Barriers, Potential Solutions, Policies, and Future Prospects. *Energies* 13 (2020) 3651. <https://doi.org/10.3390/en13143651>
13. Hannan, M.A., Wali, S.B., Ker, P.J., Rahman, M.S.A., Mansor, M., Ramachandaramurthy, V.K., Muttaqi, K.M., Mahlia, T.M.I., Dong, Z.Y. Battery Energy-Storage System: A Review of Technologies, Optimization Objectives, Constraints, Approaches, and Outstanding Issues. *Journal of Energy Storage* 42 (2021) 103023. <https://doi.org/10.1016/j.est.2021.103023>
14. Valencia, A., Hincapie, R.A., Gallego, R.A. Optimal Location, Selection, and Operation of Battery Energy Storage Systems and Renewable Distributed Generation in Medium–Low Voltage Distribution Networks. *Journal of Energy Storage* 34 (2021) 102158. <https://doi.org/10.1016/j.est.2020.102158>
15. Saini, P., Gidwani, L. An Investigation for Battery Energy Storage System Installation with Renewable Energy Resources in Distribution System by Considering Residential, Commercial and Industrial Load Models. *Journal of Energy Storage* 45 (2022) 103493. <https://doi.org/10.1016/j.est.2021.103493>
16. Come Zebra, E.I., van der Windt, H.J., Nhumaio, G., Faaij, A.P.C. A Review of Hybrid Renewable Energy Systems in Mini-Grids for Off-Grid Electrification in Developing Countries. *Renewable and Sustainable Energy Reviews* 144 (2021) 111036. <https://doi.org/10.1016/j.rser.2021.111036>
17. Wu, Y., Wu, Y., Cimen, H., Vasquez, J.C., Guerrero, J.M. Towards Collective Energy Community: Potential Roles of Microgrid and Blockchain to Go Beyond P2P Energy Trading. *Applied Energy* 314 (2022) 119003. <https://doi.org/10.1016/j.apenergy.2022.119003>
18. Soni, R., Mehta, B. Review on Asset Management of Power Transformer by Diagnosing Incipient Faults and Faults Identification Using Various Testing Methodologies. *Engineering Failure Analysis* 128 (2021) 105634. <https://doi.org/10.1016/j.engfailanal.2021.105634>
19. Jin, L., Kim, D., Abu-Siada, A. State-of-the-Art Review on Asset Management Methodologies for Oil-Immersed Power Transformers. *Electric Power Systems Research* 218 (2023) 109194. <https://doi.org/10.1016/j.epsr.2023.109194>
20. Wani, S.A., Rana, A.S., Sohail, S., Rahman, O., Parveen, S., Khan, S.A. Advances in DGA Based Condition Monitoring of Transformers: A Review. *Renewable and Sustainable Energy Reviews* 149 (2021) 111347. <https://doi.org/10.1016/j.rser.2021.111347>
21. Mogos, A.S., Liang, X., Chung, C.Y. Data-Driven Approaches for Distribution Transformer Health Monitoring: A Review. *2023 IEEE Canadian Conference on Electrical and Computer Engineering* (2023) 31–36. <https://doi.org/10.1109/CCECE58730.2023.10288844>

22. Kahouli, B., Hamdi, B., Nafla, A., Chabaane, N. Investigating the Relationship between ICT, Green Energy, Total Factor Productivity, and Ecological Footprint: Empirical Evidence from Saudi Arabia. *Energy Strategy Reviews* 42 (2022) 100871.
<https://doi.org/10.1016/j.esr.2022.100871>
23. Al-Shetwi, A.Q. Sustainable Development of Renewable Energy Integrated Power Sector: Trends, Environmental Impacts, and Recent Challenges. *Science of the Total Environment* 822 (2022) 153645.
<https://doi.org/10.1016/j.scitotenv.2022.153645>
24. Sharma, S., Sood, Y.R., Sharma, N.K., Bajaj, M., Zawbaa, H.M., Turkey, R.A., Kamel, S. Modeling and Sensitivity Analysis of Grid-Connected Hybrid Green Microgrid System. *Ain Shams Engineering Journal* 13 (2022) 101679.
<https://doi.org/10.1016/j.asej.2021.101679>
25. Elalfy, D.A., Gouda, E., Kotb, M.F., Bureš, V., Sedhom, B.E. Comprehensive Review of Energy Storage Systems Technologies, Objectives, Challenges, and Future Trends. *Energy Strategy Reviews* 54 (2024) 101482.
<https://doi.org/10.1016/j.esr.2024.101482>
26. Dehghani, F., Mohammadi, M., Karimi, M. Age-Dependent Resilience Assessment and Quantification of Distribution Systems under Extreme Weather Events. *International Journal of Electrical Power & Energy Systems* 150 (2023) 109089.
<https://doi.org/10.1016/j.ijepes.2023.109089>
27. Wang, S., Hou, Y., Guan, X., Liu, S., Huo, Z. Resiliency-Informed Optimal Scheduling of Smart Distribution Network with Urban Distributed Photovoltaic: A Stochastic P-Robust Optimization. *Energy* 313 (2024) 133449.
<https://doi.org/10.1016/j.energy.2024.133449>
28. Liang, H., Pirouzi, S. Energy Management System Based on Economic Flexi-Reliable Operation for the Smart Distribution Network Including Integrated Energy System of Hydrogen Storage and Renewable Sources. *Energy* 293 (2024) 130745.
<https://doi.org/10.1016/j.energy.2024.130745>
29. Shafiei, K., Ghassem Zadeh, S., Tarafdar Hagh, M. Planning for a Network System with Renewable Resources and Battery Energy Storage, Focused on Enhancing Resilience. *Journal of Energy Storage* 87 (2024) 111339.
<https://doi.org/10.1016/j.est.2024.111339>
30. Nair, V.J., Srivastava, P., Venkataramanan, V., et al. Resilience of the Electric Grid through Trustable IoT-Coordinated Assets. *Proceedings of the National Academy of Sciences* 122 (2025) e2413967121.
<https://doi.org/10.1073/pnas.2413967121>