

Smart Grid Strategies for Improving Reliability and Operational Efficiency of Saudi MV/LV Distribution Systems.

Abstract: The medium-voltage and low-voltage distribution networks in Saudi Arabia are now reaching a stage at which simple reinforcement on its own can no longer meet the growing demand for digital services, the increasing presence of distributed photovoltaic generation, electric-vehicle charging, bidirectional power flows, and the more complex reliability needs. This study critically brings together smart-grid strategies which can enhance reliability and operational efficiency in the Saudi medium-voltage and low-voltage systems, focusing on advanced metering infrastructure, distribution automation, fault location-isolation-service restoration, distribution phasor measurements, active voltage management, distributed energy resources, battery storage, smart charging, data-driven asset management and cybersecurity. A structured integrative review was carried out using peer-reviewed literature, giving priority to evidence from 2020 to 2025 and making use of studies that are specific to Saudi Arabia whenever available. The evidence shows that the greatest operational benefit is achieved when monitoring, communications, control and flexibility are implemented as part of an interoperable architecture rather than as separate technologies. Smart meters and high-resolution measurements increase the level of observability; automated switching reduces the time taken to restore service; coordinated control of inverters, storage systems and tap changers raises the photovoltaic hosting capacity; and managed EV charging can alleviate congestion while offering flexibility. Yet cyber exposure, data quality, interoperability, communications latency, protection coordination and the limited transferability of results based on simulation continue to be significant constraints. The review suggests a step-by-step approach to the implementation of smart-grid solutions in Saudi Arabia, focusing on observability, closed-loop automation, active network management and cyber-resilient governance. It concludes that smart-grid investments should be assessed in terms of measurable indicators relating to reliability, losses, voltage quality, asset utilisation and restoration, and that field validation should become a key priority in future research.

1. Introduction

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32 Electricity distribution is now the key operational aspect of the energy transition since new forms
33 of generation, storage, flexible demand, and digital control are increasingly connecting below the
34 transmission system. In Saudi Arabia this shift is especially important for the medium-voltage
35 and low-voltage networks that serve quickly expanding urban areas, industrial sites, commercial
36 energy use and domestic customers. A national smart-grid strategy must therefore achieve two
37 closely related aims: maintaining a reliable supply under more variable operating conditions and
38 obtaining greater capacity and efficiency from the existing network assets. A conceptual review
39 focused on Saudi Arabia identifies smart energy, communication and information infrastructures
40 as mutually dependent foundations for the country's smart-grid development [1], while recent
41 analysis of the deployment of distributed photovoltaics points out both the economic advantages
42 and the technical limitations connected with greater adoption of photovoltaics on roofs and
43 behind the meter [2].

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45 The issue involved is not merely the inclusion of renewable energy sources. High levels of PV
46 installation can cause the direction of power flow on feeders to reverse, lead to increases in
47 customer voltages, affect the protection margins, and result in a greater number of operating
48 states having to be taken into account. Case studies carried out in Saudi Arabia have
49 demonstrated that measures to counter voltage rises must involve coordinated control rather than
50 relying on passive assumptions about the network [3], and a large-scale study of PV connected to
51 the Saudi grid has shown the need for harmonic assessment and filtering in order to comply with
52 power-quality standards [4]. Similarly, dynamic reactive-power support has been looked at
53 within a Saudi PV context in order to improve voltage performance [5], while research into the
54 design of residential PV systems has emphasised the need to comply with Saudi interconnection
55 requirements, including those relating to power quality, ride-through behaviour and the use of
56 modest battery storage [6]. Together, these studies explain why distribution reliability and
57 operational efficiency should be regarded as control problems as well as planning problems.

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The other aspect is the electrification of transport together with flexible demand. If EV charging is not properly managed it can result in transformer overload, phase imbalance, voltage deviation and local congestion. Recent reviews have indicated that the measures needed to alleviate these problems rely on coordinated charging, the use of storage, distributed generation and optimisation rather than on a single intervention at the device level [7-9]. The same digitalisation which makes it possible to implement these strategies also leads to security dependencies. Smart-grid charging coordination can be affected by false data, proving that control performance and cyber integrity are closely linked [10]. It therefore follows that the Saudi MV/LV modernisation programme must integrate electrical engineering, communications, data governance and operational security.

The review is concerned with practical smart-grid strategies at the distribution level and makes a distinction between reliability—defined as the ability to avoid, endure and quickly recover from interruptions and abnormal conditions—and operational efficiency, which means lower losses, better voltage regulation, improved use of assets, less manual intervention and a more economical way of deploying flexibility. The main point put forward is that these results are the outcome of a closed-loop architecture: detect network conditions, estimate and diagnose the state of the system, optimise the corrective action, carry out the control via field devices, and then learn from the actual performance. Figure 1 shows this architecture in the case of a Saudi MV/LV setup. The rest of the paper looks at the technologies that enable each layer, the evidence in support of them, the way in which they interact and the research needed for a credible large-scale implementation.

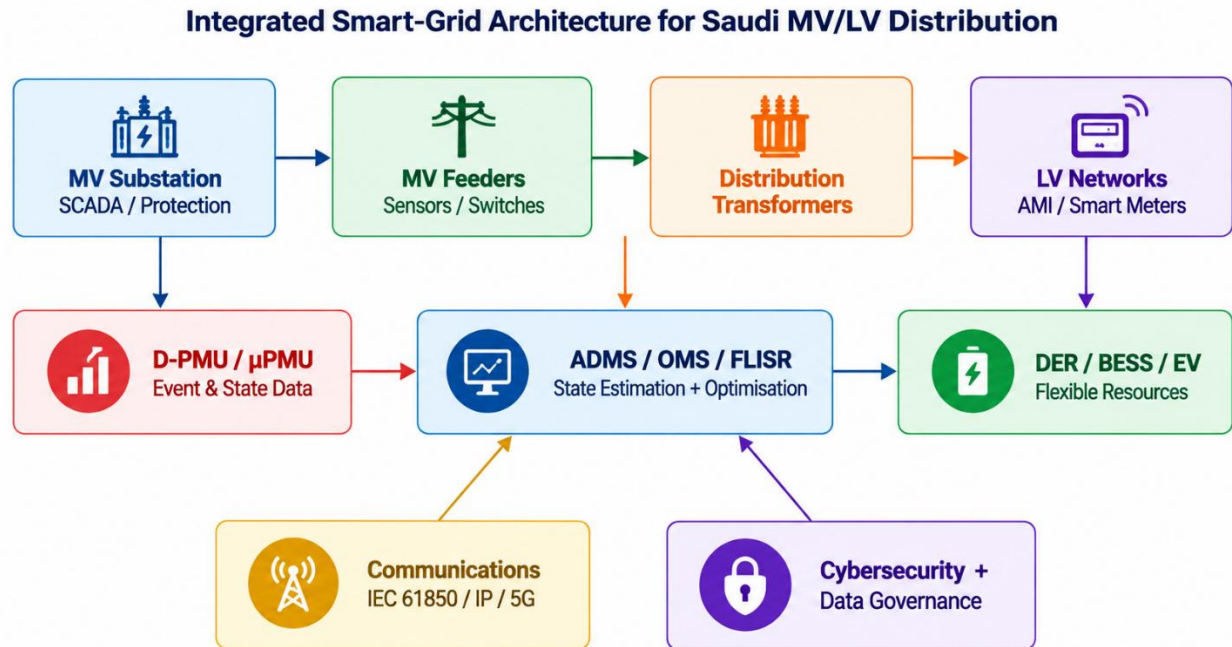


Figure 1. Integrated smart-grid architecture for Saudi MV/LV distribution systems.

2. Aim of the Study

This review seeks to critically assess the extent to which smart-grid technologies and operating strategies can enhance the reliability and operational efficiency of the MV/LV distribution systems in Saudi Arabia. Instead of looking at the various technologies separately, the study looks at the way in which measurement, automation, flexibility, optimisation and cybersecurity can be combined into a coherent distribution-management framework that is technically appropriate for networks that have a higher level of penetration of PV systems, storage, EV charging and digitally controlled loads.

3. Research Objectives

We should identify the most important problems relating to reliability and efficiency that arise as a result of the active operation of the Saudi MV/LV networks. The evidence concerning

advanced metering, distribution automation, synchrophasor measurements, active voltage management, coordination of distributed energy resources, and controlled electric vehicle charging must be assessed. A comparison should be made of the advantages, dependencies, and limitations that these smart-grid techniques have for operations. The requirements regarding cybersecurity, data quality, interoperability, and communications which are necessary for reliable automation should be investigated. A research programme together with a staged implementation approach, one that is linked to measurable distribution-system performance indicators, should be developed.

4. Research Questions

The review is based on four closely related research questions: what smart-grid approaches offer the most solid technological basis for enhancing reliability and operational efficiency in medium-voltage and low-voltage distribution networks; how sensing technologies, automation, the flexibility of distributed energy resources, and electric vehicle charging should be incorporated into the situation in Saudi Arabia; what technical, cybersecurity, and organisational constraints might prevent the realization of the expected smart-grid benefits; and which evidence gaps need to be resolved before large-scale deployment, benchmarking, and performance evaluation can take place across the Saudi distribution networks.

5. Review Methodology

The period 2020 to 2025 was chosen as the preferred publication window since digitalisation of distribution and the integration of distributed energy resources have developed rapidly, even though a smart-meter fault-detection study from 2019 was included because it directly shows an application of distribution-level reliability that is not completely covered by the more recent literature [11]. In order to be included, the studies had to be published in a peer-reviewed journal, have a clear relevance to distribution operation or to smart-grid enabling infrastructure, include a

sufficiently detailed description of the methods or a synthesis, and make a direct contribution to at least one of the review themes. Preference was given to Saudi-specific evidence where this was available. International studies were included if they dealt with distribution functions that could be transferred such as fault location, voltage regulation, hosting capacity, smart charging or cyber protection.

The screening process was qualitative and not based on artificially generated PRISMA counts. First, the titles and abstracts were examined to determine if they were functionally relevant; afterwards, the full texts or the publisher's records were reviewed to check the distribution level investigated, the technology used, the performance variables, and the assumptions and limitations. The methodological quality was evaluated on the basis of five criteria: the clarity of the system boundaries; the adequacy of the description of the network, the data or the simulation; the transparency of the performance metrics; the realism of the operating constraints; and whether the conclusions were in proportion to the evidence.

The set of final references consists of precisely 30 items, 29 of which were published between 2020 and 2025 and one date from 2019. The synthesis was structured according to six operational functions: observability; fault management and restoration; voltage, loss and hosting-capacity control; coordination of distributed energy resources and storage; EV flexibility; and cyber-resilient communications and analytics. Since the study designs, the feeders, the levels of penetration and the objective functions vary, the findings were not combined by means of statistical pooling. Rather, a thematic comparison was carried out, with the aim of separating out the technical mechanisms that had been demonstrated from the more general claims regarding applicability. The DOI metadata were verified against the publisher's records or against those in Crossref or other authoritative bibliographic databases, and in the reference list each DOI is given as an executable <https://doi.org> link.

There are two intentional safeguards designed to prevent overstatement. The first of these is that the results obtained from the standard test feeders are regarded as showing that the algorithm is

feasible rather than as proof that it works in the Saudi field. The second is that the Saudi case studies are examined in the context of the network or project conditions stated for them and are not taken as representing general national operating statistics. As a result, the review that is produced is a critical synthesis of the evidence together with an implementation framework, not a numerical meta-analysis.

6. Thematic Literature Review and Critical Analysis

6.1 Observability through AMI, smart meters and distribution synchrophasors

Automation can only begin when the state of the network is known at an adequate spatial and temporal resolution. Since smart meters offer voltage, energy and event data at the low-voltage level, they are able to support a range of functions in addition to billing. Vieira et al. showed that voltage unbalance data obtained from low-voltage smart meters can help with the detection and location of series high-impedance faults, thus demonstrating how the existing metering infrastructure can function as a reliability sensor [11]. Further research into fault location confirms that quick localisation is essential to restoration performance, but also indicates that accuracy is dependent on the network models, the location of the measurements, the behaviour of distributed generation and the availability of communications [12]. The main design issue therefore for utility companies in Saudi Arabia is not whether smart meters should collect more data, but rather which operational functions are justified by the required data rates, retention times, latencies and quality.

High-resolution synchrophasor measurements provide an additional, complementary level of information. The use of distribution PMUs and micro-PMUs enables synchronized voltage-angle data to be obtained, which in turn improves state awareness, event detection and the validation of models in active feeders [13,14]. The benefit of these devices is greatest when they are installed at electrically significant locations rather than when deployed without regard to location. A

feasible setup involves combining wide-reaching AMI coverage with D-PMUs placed at substations, at major laterals, at DER clusters and at key industrial sites. This kind of combined approach lowers the instrumentation costs while still giving the ADMS sufficient observability to be able to tell the difference between load variations, reverse flow, voltage-control interactions and abnormal events.

6.2 Distribution automation, fault management and service restoration

Observability will only lead to an improvement in reliability if it results in prompt action. Distribution automation achieves this by combining remotely controlled switchgear, feeder indicators, protection information, and network models in order to detect faults, isolate the damaged sections, and restore the healthy loads. As shown in the literature concerning fault prediction and location, smart-grid methods are increasingly making use of synchronized measurements, state estimation, signal processing and data-driven classifiers in order to reduce the search space and restoration delay [12]. In the case of Saudi MV networks, automated switching can be particularly valuable on feeders where manual patrol and switching would otherwise cause the outage to last longer; however, the advantages depend on an accurate topology, reliable telecommunications, and proper protection coordination following reconfiguration.

Automation should thus be considered as a series of steps rather than as a collection of individual devices: detection, validation, isolation, checking whether switching is feasible, carrying out restoration and then verifying the situation after the event. False positives may result in unnecessary switching, and out-of-date topology data might cause an otherwise optimal restoration plan to be invalidated. A cyber-physical viewpoint is essential since a communication failure can have the same operational effect as the loss of a field device. The most realistic implementation approach is progressive closed-loop automation: start with advisory fault location, check this against operator experience, automate isolation within clearly defined

contingencies, and only then allow for wider self-healing restoration. This helps to reduce operational risk and produces local evidence before greater levels of autonomy are introduced.

6.3 Active voltage management, loss reduction and PV hosting capacity

The adoption of distributed photovoltaics is a key factor in shifting from passive voltage regulation to active network management. Evidence from Saudi Arabia has already shown the technical importance of voltage rise, reactive power control, harmonics, and compliance with the grid code [3-6]. Although traditional measures such as reinforcing conductors are still important, smart-grid control can delay or address the need for such reinforcement by coordinating the use of on-load tap changers, capacitor banks, smart inverters, and storage. Khan et al. demonstrated that coordinated control of the OLTC and battery systems can reduce voltage violations while at the same time limiting excessive cycling of the storage, thus showing the benefit of assigning different timescales to slow and fast voltage resources [15].

Hosting capacity serves as a useful link between planning and operation since it shows the amount of distributed energy resources or electric vehicle load that can be connected without exceeding voltage, thermal, protection, or power quality limits. Although recent reviews stress that hosting capacity is not a fixed number of feeders but rather depends on load conditions, resource output, control measures, and the method of assessment [9,16], for low-voltage systems in Saudi Arabia with increasing rooftop photovoltaics, static worst-case limits could become unnecessarily conservative if smart inverters, export control, battery energy storage systems, and the time-varying capability of the network are available. On the other hand, overly optimistic estimates of hosting capacity are unsafe if harmonic limits, unbalance, protection sensitivity, or data uncertainty are neglected. Hosting capacity should therefore be managed actively by making use of validated network models, time-series measurements, and clearly defined operational envelopes.

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239 Table 1 compares the main smart-grid strategies and their relevance to Saudi MV/LV systems.
240 The comparison shows a consistent pattern whereby strategies which seem independent when
241 looked at at the device level end up being mutually dependent in practice. For example, the
242 settings of smart inverters require voltage observability; automated restoration demands a
243 reliable topology; predictive maintenance needs data on assets and events; and EV flexibility
244 depends on communications, tariffs or control agreements. Reliability is thus an architectural
245 property and not merely the result of the smart devices that have been installed.

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247 Table 1. Comparative smart-grid strategies for Saudi MV/LV reliability and operational
248 efficiency.

Strategy	Primary mechanism	Reliability / efficiency contribution	Saudi MV/LV implementation priority
AMI + smart-meter analytics	Customer-edge voltage, event and energy visibility	Faster anomaly detection; voltage-quality evidence; loss and loading insight	Use AMI as an operational sensor layer, not only for billing; define data quality and latency classes.
FLISR + remote switching	Automated fault detection, isolation and restoration	Shorter restoration time; fewer manual switching steps; improved supply continuity	Deploy progressively on feeders with dependable topology, telecoms and remotely operable switchgear.

Strategy	Primary mechanism	Reliability / efficiency contribution	Saudi MV/LV implementation priority
D-PMU / μ PMU	Time-synchronised phasor measurements	Improved state estimation, event detection and model validation	Target substations, DER clusters and critical nodes; integrate with AMI rather than duplicate coverage.
Active voltage control	Coordinated OLTC, capacitors, smart inverters and BESS	Reduced voltage violations; higher PV hosting capacity; better asset utilisation	Coordinate slow and fast controls; validate inverter and BESS limits under Saudi feeder conditions.
Managed EV charging	Time- and location-aware charging limits; optional V2G	Peak and congestion reduction; flexible demand; possible ancillary support	Begin with unidirectional managed charging tied to transformer/feeder constraints; expand to V2G selectively.
Cyber-resilient ADMS	Identity, segmentation, secure communications, anomaly detection	Protects measurement integrity and control availability; limits common-mode digital failures	Embed security lifecycle requirements in procurement, commissioning, patching and incident recovery.

6.4 DER, storage and active distribution management

Battery energy storage is capable of supporting voltage regulation, reducing peak demand, alleviating congestion, enabling islanding and facilitating restoration, but its value is determined by coordinated scheduling. Research involving microgrids and active distribution systems indicates that storage systems and controllable distributed energy resources should be dispatched in order to achieve a number of different objectives rather than simply following an energy-arbitrage signal [22-24]. Although data-driven management can enhance forecasting and enable adaptive operation, the literature also cautions that models developed based on limited operating conditions may fail to generalise to rare faults or to quickly changing asset states [24]. Storage control in the context of Saudi Arabia therefore ought to maintain a level of reliability reserves for contingencies rather than fully allocating its capacity to economic optimisation.

The idea of an active distribution network also alters the role of the distribution operator. Instead of having to accept fixed amounts of power injection and load, the operator can make use of flexibility contracts, inverter functions, demand response and storage schedules in order to keep voltages and the thermal loading within acceptable limits. The real challenge lies in coordinating actions over different time scales. It is not possible for a single, all-encompassing optimiser to handle millisecond protection, sub-second inverter control, minute-level voltage optimisation, hourly storage scheduling and day-ahead forecasts. A hierarchical control system is therefore more realistic: local devices enforce the fast safety limits, the feeder controllers co-ordinate voltage and congestion, and the ADMS handles the optimisation of wider network objectives.

6.5 EV charging as a controllable LV load and flexibility resource

The use of electric vehicle chargers presents both risks and opportunities for the local distribution system. If a large number of chargers are in use at the same time, this can lead to increased peak loads and cause local voltage and phase-balance issues. Tayri and Ma combine

these effects and indicate that smart charging, vehicle-to-grid (V2G), the use of storage systems and the integration of renewable energy are repeated strategies for mitigating such problems [7]. Studies on allocation also show that the location of chargers affects network losses, voltage profiles and the demand for capacity [17]. Li and Jenn prove at a system level that charging demand can have a substantial impact on distribution congestion, thus underscoring the importance of modelling not just the annual energy demand but also where and when charging takes place [18].

Managed charging is able to move demand away from the busy periods, and V2G can offer extra flexibility in cases where battery degradation, user involvement and the market structure are acceptable. Research into shared electric vehicles, robust scheduling and smart charging at the national level shows the technical possibility of reducing congestion and the need for storage [19-21]. Further, optimisation of microgrids suggests that with coordinated demand response, electric vehicles and storage it is possible to lower operating costs and network losses when facing uncertainty [22,23]. Other charging structures such as battery swapping and more extensive reviews of EV integration also highlight the need to treat the assessment of infrastructure, grid effects and coordination with renewables as a single planning issue [26-28]. Nevertheless, the implementation in Saudi Arabia should not assume that all chargers are continuously controllable. Effective programmes will require customer segmentation, charger interoperability, the option to opt out, attention to cybersecurity and consideration of local transformer limitations. The immediate priority therefore should be managed unidirectional charging with feeder-aware limits; V2G can be introduced later in those cases where viable business models justify the extra complexity.

6.6 Cybersecurity, data integrity and interoperable control

An automated distribution grid has a greater digital attack surface. Research into smart-grid security in Saudi Arabia has pointed out the need for specific controls regarding bidirectional IoT information flows [29]. General reviews identify attacks on hardware, software,

communications, and data, indicating that failures in availability and integrity can have a direct impact on grid operations [30]. The significance for MV/LV control is clear: false measurements can mislead state estimation, fraudulent commands can alter switching states, and compromised chargers or inverters can combine to cause a system-wide disturbance. Elshazly et al. give a concrete example in which false data can be used to manipulate reinforcement-learning charging coordination, proving that optimisation algorithms cannot be assessed separately from adverse data conditions [10].

Automation should therefore have cybersecurity built into it from the start rather than having it added on after the system has been deployed. The essential principles are authenticated device identity, the use of encrypted communications where this is operationally possible, least-privilege access, network segmentation, secure configuration management, event logging, firmware governance and the ability to detect anomalies. Just as important is graceful degradation: if wide-area communications or cloud analytics are not available, then essential protection measures and safe local control should still be maintained. This supports the use of architectures which keep deterministic local functions while making use of centralised intelligence for optimisation, coordination and learning. This kind of separation also enhances maintainability since software upgrades can be tested without putting the basic feeder protection at risk. Operational importance should also be given to standards-based interoperability; research into energy management based on IEC 61850 shows how distributed generators and EV resources can be coordinated during abnormal conditions when communications and device models are explicitly structured [25].

7. Discussion

The evidence shows that there is no single smart-grid technology which is able to reliably achieve both greater reliability and higher operational efficiency; while AMI enhances observability it does not restore the supply, automated switches reduce the duration of outages but may operate incorrectly if the topology or the measurements are inaccurate, smart inverters

offer more voltage flexibility but require coordinated settings, and batteries can provide rapid control yet may be drained by purely economic dispatch. The most effective approach is therefore to carry out functional integration based on a distribution-management platform that keeps a trusted network model and coordinates the devices according to timescale and priority.

For the Saudi MV/LV systems there are four stages of implementation. The first of these is ensuring measurement integrity, which involves validated feeder models, AMI voltage data, substation telemetry and the selective use of D-PMUs. The second stage is reliable automation, comprising remote switching, fault indicators, integration with outage management and staged FLISR. The third is active network management, covering co-ordinated OLTC action, reactive power from inverters, BESS, demand response and the use of dynamic operating envelopes for PV and EV connections. The fourth is cyber-resilient optimisation, consisting of forecasting, anomaly detection, asset analytics and adaptive scheduling, all of which are protected by identity, segmentation and secure lifecycle management. Figure 2 shows the resulting closed-loop framework.

The literature also shows a distinction between what is technically possible and what has real deployable value. Although many optimisation studies make use of IEEE test feeders, synthetic load profiles or perfect communication conditions, these are suitable for the purpose of developing algorithms but do not provide information on performance under the temperature extremes found in Saudi Arabia, in relation to heterogeneous feeder designs, the stress on equipment caused by dust, in communication dead zones, in relation to rapidly growing urban loads or with respect to utility-specific protection practices. As a result, investment decisions should require field KPIs and reliability improvements should be judged in terms of interruption frequency and duration, restoration time and the success of automated isolation. Efficiency should be measured by means of technical losses, peak loading, voltage violations, switching operations, transformer utilisation and deferred reinforcement, and cyber performance should involve patch compliance, authentication coverage, detection latency and recovery testing.

Another consequence is related to organisational integration. Since distribution planning, protection, operations, telecoms, cybersecurity and customer programmes usually make use of different data and follow separate decision cycles, the value of the smart grid is diminished if these functions stay apart. Hosted-capacity studies require real switching states and voltage data; EV programmes need to know the transformer constraints; cyber teams require a list of the field assets; and planners need event data in order to spot weak feeders. It is therefore just as important as the use of advanced algorithms to have a common information model and a governed data architecture. The Saudi approach should therefore focus on interoperable platforms and on repeatable operating procedures rather than on technology demonstrations which cannot be scaled across vendors or regions.

The order in which implementation steps are taken should also take into account the fact that reliability value builds up as a result of the interactions between the various operational layers. Improved sensing increases confidence in the topology and in the ability to diagnose faults; better diagnosis allows for faster switching; faster switching in turn reduces the duration of outages; and more detailed records of events help with future planning and maintenance decisions. The same kind of feedback effect applies to efficiency. Voltage measurements allow for more accurate inverter and tap control, which boosts the amount of capacity that can be used and may lessen unnecessary curtailment or the need for reinforcement. Pilot programmes therefore ought to be designed in such a way as to capture the benefits that arise across different functions rather than just report on the performance of individual devices. This kind of systemic viewpoint is especially important in cases where the procurement packages divide the responsibilities for meters, communications, automation, analytics and cybersecurity among different suppliers. Before commissioning, the technical interfaces, the time synchronisation, the naming conventions, the assignment of models and the responsibility for failed control actions should all be defined. Otherwise, local optimisations could lead to inconsistencies across the system as a whole and the expected benefits of digitalisation could be undermined by integration problems.

The Saudi programme for deploying equipment should also take the different types of feeder networks into account before allocating technology. Feeder types such as dense urban cable networks, long radial overhead feeders, industrial areas and mixed residential circuits all have different requirements when it comes to reliability, communication limitations and flexibility. In the case of urban networks, dense automation is justified since the high concentration of customers makes quick isolation and restoration more valuable, while in remote feeders greater advantages can be derived from robust communications, sectionalising points and focused condition monitoring. For industrial feeders it is necessary to pay particular attention to voltage quality, the sensitivity of processes and the selectivity of protection, and for residential low-voltage networks phase-level visibility is required because roof-mounted PV systems and single-phase EV charging can cause serious localised problems. It is therefore more reasonable to adopt a portfolio approach than to have a single nationwide specification.

It is also necessary to treat avoided failures separately from faster recovery. While predictive asset analytics can lower the probability of equipment failure provided that sufficient data are captured to detect degradation, FLISR mainly serves to reduce the impact on the customer after a fault has taken place. The benefits should therefore not be combined into a single general reliability claim. In a similar way, loss reduction, peak shaving and deferred reinforcement are different efficiency measures each requiring separate evidence. A project which reduces peak transformer loading can still generate considerable planning value even if the annual energy losses only change slightly. Benefit cases must therefore link each control action to a measurable physical mechanism and then on to an economic or reliability outcome.

In the end, governance must involve clear model-validation and change-management procedures. Since customers connect PV systems, chargers and storage, switching states change and network reinforcement modifies the impedance and protection settings, distribution models tend to drift. Automated control based on an outdated model may result in confident but wrong decisions. Utilities should carry out regular checks of the topology, reconcile the parameters, perform clock-synchronisation checks, calibrate the sensors and conduct reviews after events. The algorithms should be versioned, tested using typical scenarios and kept under observation for any

decline in performance after they have been put into use. By adopting these practices, digital infrastructure becomes an operational capability rather than just a set of devices, and they provide a structured approach for scaling up successful pilot projects throughout the Saudi distribution areas. They also enable regulators and utility managers to compare investments in a consistent manner, to detect incorrect benefit assumptions at an early stage, and to redirect capital towards interventions which show repeatable network performance in actual operation. This level of discipline also facilitates transparent benchmarking between pilot feeders and subsequent deployments.

Closed-Loop Reliability and Operational-Efficiency Framework

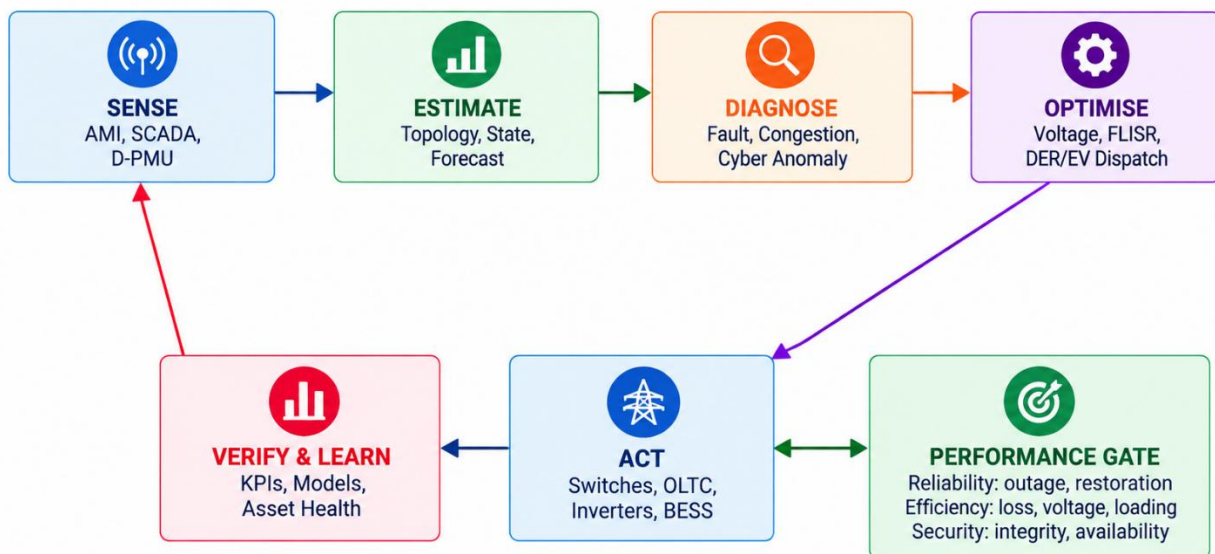


Figure 2. Closed-loop framework linking sensing, diagnosis, optimisation, control and measurable performance.

8. Research Gaps and Future Research

There are four areas that should be given priority. First, research into Saudi Arabia's distribution system should obtain more field data that links AMI voltage levels, feeder loading, outage

events, switching records, PV output, and asset condition. Otherwise, it will not be possible to adjust the algorithms to take account of the diversity of local operating conditions. Second, hosting-capacity and EV studies should shift from static snapshots to probabilistic, time-series and phase-specific analyses which take into consideration inverter controls, customer behaviour and changes in topology. Third, reliability research should assess the performance of an integrated FLISR, storage and DER system under communication failures and during cyberattacks, not just in normal operating conditions. Since cybersecurity research has already demonstrated that the increasing connection of grids leads to coupled vulnerabilities in both information and control systems, conventional reliability models might fail to identify them [29,30].

Fourthly, greater attention should be paid to implementation economics and the interaction between control systems. The fact that a measure has a technical benefit does not mean that extensive instrumentation, storage facilities or communications upgrades should automatically be carried out. In future pilot projects, the various architectural alternatives should be compared with regard to their lifecycle cost, their ability to reduce outages, the savings from losses, the impact of deferred reinforcement and maintainability. Research should also examine how the local inverter controls interact with feeder-level voltage optimisation and how different flexibility services compete for the same battery or EV capacity. The use of standardised Saudi test feeders, anonymised utility datasets and reproducible digital-twin environments would greatly enhance the comparability of studies.

9. Practical, Managerial and Policy Implications

A carefully planned method of implementation can turn the evidence under review into practical application. In the first stage, the data foundations should be set up by verifying feeder connectivity, establishing asset registers, assessing smart-meter voltage quality, obtaining synchronized substation measurements, and monitoring communications health. In the second stage, high-value reliability functions should be automated on certain feeders, specifically

470 regarding remote switching, fault location, and operator-assisted restoration. In the third stage,
471 active voltage and flexibility management should be introduced in areas where there is
472 significant penetration of PV, storage or EVs. In the fourth stage, advanced analytics should only
473 be scaled once enough local data are available to validate the models and to detect any
474 performance drift.

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476 When it comes to management, projects must be approved based on specific benefit mechanisms
477 rather than on general "smart" capabilities. For a D-PMU project it is necessary to state exactly
478 which state-estimation or event-detection problem it is intended to solve; for a BESS project it
479 should specify the reserved capacity for reliability services; and for an EV-control programme it
480 should name the feeder or transformer constraints that it will handle. Table 2 gives a practical
481 roadmap showing the relationship between the various implementation layers and the relevant
482 KPIs and governance requirements.

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484 Policy and regulatory measures can support this method by calling for interoperable inverter and
485 charger functions, the ability to receive secure remote updates, standardised data exchange and
486 transparent connection studies. Dynamic connection limits should only be introduced in those
487 cases where the reliability of measurement and control is sufficient to enforce them. Customer
488 flexibility schemes should specify customers' consent, their privacy rights, their right to override
489 and the issue of compensation. Such measures help to make certain that improvements in
490 operational efficiency do not come at the cost of customer autonomy or system security.

Table 2. Staged implementation roadmap and measurable performance indicators.

Implementation layer	Key actions	Core KPIs	Governance / risk control
1. Data foundation	Validate topology; AMI voltage use; telemetry and time synchronisation; communications health	Missing-data rate; model accuracy; voltage visibility; telemetry availability	Data ownership; naming standards; clock quality; secure device inventory
2. Reliability automation	Remote switching; fault indicators; OMS integration; staged FLISR	Fault-location time; restoration time; successful isolation; switching accuracy	Operator override; contingency validation; protection coordination; fallback modes

Implementation layer	Key actions	Core KPIs	Governance / risk control
3. Active network management	OLTC/inverter/BESS coordination; dynamic hosting; demand response; managed EV charging	Voltage violations; losses; peak loading; curtailment; hosting capacity	Control envelopes; customer agreements; BESS reserve policy; interoperability
4. Advanced analytics and resilience	Forecasting; anomaly detection; predictive maintenance; cyber-physical testing	Forecast error; anomaly detection latency; asset failures; cyber recovery time	Model monitoring; patch governance; segmentation; incident response exercises

10. Limitations

The review is constrained by the variety existing among feeders, climates, levels of penetration, optimisation objectives and performance metrics. Although peer-reviewed evidence specific to Saudi Arabia is increasing it is still smaller in amount than the international literature and therefore some of the conclusions are based on mechanisms that can be transferred rather than on actual field observations in the region. The study does not carry out a quantitative meta-analysis and does not make any claims regarding improvements in national reliability as a result of individual case studies. It also concentrates on distribution operation rather than on transmission expansion or on the design of the wholesale market. Lastly, since inverter standards, EV technology, communications systems and cyber threats are all changing rapidly, guidance for implementation should be updated as new field evidence and regulations become available.

11. Conclusion

The modernisation of the smart grid has the potential to greatly improve the reliability and operational efficiency of Saudi Arabia's medium and low voltage distribution systems, provided that the technologies are integrated around reliable operating functions. The relevant literature indicates that progress should be made from improved observability using AMI and a selection of synchrophasors, through to automated fault management, active voltage control, coordination of distributed energy resources and storage, and controlled EV charging. Studies into photovoltaics in Saudi Arabia confirm that existing constraints relating to voltage, power quality and interconnection already call for a more active approach to distribution management, and wider evidence shows that hosting capacity and congestion can be reduced when flexible resources are coordinated rather than being treated as uncontrolled injections or loads.

The key lesson concerning implementation is architectural in nature: measurement quality, network models, communications, field automation, optimisation and cybersecurity all need to be designed as part of a single closed loop, including safe local fallback options. Efficiency improvements should be assessed by looking at losses, voltage performance, peak loading and the level of asset utilisation; meanwhile, gains in reliability should be measured using indicators relating to interruption, restoration and successful isolation. Future efforts should focus on carrying out field trials in Saudi Arabia, using reproducible datasets, carrying out probabilistic hosting-capacity analysis, testing cyber-physical restoration and conducting a lifecycle economic evaluation. Having put in place these precautions, smart-grid investment can progress from simple device deployment to an evidence-based mode of operation in which distribution networks become more observable, flexible, resilient and efficient as electrification and distributed energy resources increase.

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