Digital Transformation of Electrical Transmission Infrastructure Through Smart Grid Technologies: A Saudi Vision 2030 Perspective.

Abstract:

Electricity transmission networks are changing from being based on individual assets to becoming systems that can be observed digitally, are driven by data and are becoming more adaptive. This shift is particularly important for Saudi Arabia, since the rapid expansion of renewable energy, the great distances across the country, the emergence of new industrial loads and the aims set out in Vision 2030 all mean that the transmission system has to handle greater variability without compromising reliability. This review carefully brings together 30 peer-reviewed studies that were published between 2020 and 2025 in order to look at how smart grid technologies can help with the digital transformation of the transmission infrastructure. The evidence is grouped into five interrelated areas of capability: wide-area observability and digital substations; high-performance communications and edge-cloud computing; artificial intelligence and advanced analytics; digital twins and condition-based asset management; and flexibility technologies backed by storage, demand response and grid-enhancing measures. The review concludes that value is not obtained simply by acquiring individual technologies; instead, the benefits come about through the use of interoperable data models, time-synchronized measurements, cyber-resilient communication, validated analytics, coordinated control and governance structures that enable reliable operational decisions to be made on the basis of data. In the case of Saudi Arabia, the most promising approach is a step-by-step transformation which first builds a solid foundation of trusted sensing and data, then incorporates analytics and digital twins, and finally extends closed-loop and predictive functions under human supervision. The paper puts forward a transmission-specific architecture and an implementation roadmap in line with Vision 2030, points out the gaps in the existing evidence regarding operations in desert conditions and along large-scale renewable energy corridors, and establishes research priorities in the areas of explainable artificial intelligence, cyber-physical resilience, digital-twin validation and performance-based investment appraisal.

Keywords: Smart grid; electrical transmission; digital transformation; Saudi Arabia; Vision 2030; synchrophasors; digital twins; artificial intelligence; grid resilience

1. **Introduction**

The era in which physical reinforcement and digital modernization can no longer be regarded as separate planning issues has now arrived. Traditional transmission networks were based on fairly predictable large-scale power generation, involved one-way power flows and made use of supervisory systems which supplied sufficient information at the speed needed by electromechanical equipment. The current grids, however, operate in a different environment. The integration of variable renewable energy sources causes power-flow patterns to change on a shorter time scale, converter-connected resources modify the system's dynamics, major industrial and urban developments result in demand that is geographically concentrated, and the expectations with regard to reliability now call for faster detection of disturbances and coordinated corrective measures. In response to these demands, smart grid technologies address the situation by integrating sensing, communication, computing, analytics and control throughout the transmission system rather than by introducing just one device or software layer [1,2].

The latest literature refers to the smart grid as a data-intensive cyber-physical system in which the quality of measurements, the communication systems, the analytics and the operational governance all rely on one another [3]. This way of looking at things is crucial for the transmission sector since a digital platform which generates more data without improving state awareness, asset decisions or system security might lead to greater complexity without enhancing value. On the other hand, a well-designed digital architecture can increase the usable capacity of the existing assets, enhance situational awareness, facilitate the integration of renewable energy and allow for earlier intervention when equipment or network conditions worsen. Saudi Arabia offers a strategically important context in which to examine this shift. The country's power system has to meet the demands of economic diversification, the development of new cities and industries, rising levels of electrification and a rapidly changing generation mix.

Reviews focused on Saudi Arabia identify smart grid development and the integration of renewables as key elements of this broader transition, while also stressing the importance of having compatible infrastructure, system flexibility and institutional coordination [4]. The integration of renewable energy increases the value of forecasting, flexibility, storage and the coordinated exchange of information between different layers of the grid [5-7].

The literature is still fragmented, with certain studies concentrating on phasor measurement units, others on communication networks, some on artificial intelligence, and still others on digital twins, storage or cybersecurity. While this kind of specialisation helps to improve individual technologies it does not make it easy to see the sequence of implementation that is required by a transmission utility. There is also a problem relating to context: it is not possible to automatically transfer evidence obtained from distribution grids, microgrids or from mature liberalised markets to a national transmission system which has different climate conditions, a different scale, different governance arrangements and different investment features. In order to overcome these limitations, this review regards digital transformation as a capability-building process rather than as a list of technologies and it examines how sensing, communication, analytics, asset intelligence, flexibility and governance can be combined into a coherent Saudi transmission strategy, as well as identifying where the current evidence is still too weak to allow for confident large-scale deployment.

2. Aim, Objectives and Research Questions

This review seeks to create a comprehensive, transmission-specific understanding of the role that smart grid technologies can play in achieving the digital transformation of Saudi Arabia's electrical transmission infrastructure as part of Vision 2030. The synthesis is guided by four objectives: first, to determine which digital capabilities are most relevant to transmission planning, operation and asset management; second, to examine how these capabilities interact rather than to consider them as separate technologies; third, to look at the technical, cyber, organizational and contextual barriers that might hinder their implementation in Saudi Arabia;

and fourth, to develop a staged transformation framework that connects technology investment with measurable transmission outcomes.

The review looks at four questions: which smart grid technologies offer the most obvious benefits at the transmission level? How should data, communications, analytics and control be combined in order to achieve a reliable operational capability? Which obstacles are most significant in the Saudi situation? And what research and implementation priorities are needed if we are to move from having digitised assets to an adaptive and cyber-resilient transmission system by 2030?

3. Review Methodology

A structured integrative review approach was chosen since the research problem involves various fields such as electrical engineering, communications, data science, asset management and energy policy. The searches were carried out from January 2020 to December 2025. The main sources used for discovering the literature were Scopus, the Web of Science Core Collection, IEEE Xplore and ScienceDirect. The search strings combined terms such as "smart grid", "transmission grid", "synchrophasor", "PMU", "wide-area monitoring", "digital substation", "IEC 61850", "edge computing", "artificial intelligence", "machine learning", "digital twin", "asset condition monitoring", "grid cybersecurity", "energy storage", "grid-enhancing technologies", "renewable integration", "Saudi Arabia" and "Vision 2030".

In order to be included, a study had to have been published in an English-language, peer-reviewed journal during the specified period, have a direct connection with one or more of the transmission capabilities, and include a resolvable digital object identifier. Saudi research into energy transition was included if it provided information on transmission needs, even if the study's main area of focus was the broader energy system. Any studies that were concerned only with household automation or distribution applications were excluded unless they offered an architecture or method that was clearly transferable to transmission; in such cases, the limitation is stated clearly. Papers presented at conferences, editorials, duplicate entries and articles that did not contain adequate methodological details were all excluded. The final analytical corpus consisted of 30 studies which had been verified by means of their DOI and were selected on the grounds of their depth, complementarity and relevance.

The assessment of quality took into account the clarity of the method, the adequacy of the technical description, the strength of the evidence, reproducibility, the explicit discussion of limitations, and the relevance to operation at a transmission scale. The evidence was grouped into seven themes: observability and synchronized measurement; digital substations and communications; edge-cloud computing; artificial intelligence and decision support; digital twins and asset management; flexibility and the integration of renewable energy; and cybersecurity, interoperability and governance. The synthesis then examined the enabling relationships between the themes. It focused on the combinations which are necessary as prerequisites for reliable operational use. It did not include any unverified screening totals or statistical claims. The resulting framework is interpretive and geared towards engineering: it establishes a defensible sequence for the development of capabilities while retaining uncertainty in cases where the published evidence is specific to a context or is still emerging.

4. Digital Architecture of Smart Transmission Infrastructure

A necessary first step in the digital transformation of the transmission network is to achieve trustworthy observability. Synchrophasor technology enables time-aligned voltage and current phasors to show inter-area oscillations, angle separation, frequency behaviour and the way disturbances spread, at a level of resolution that cannot be obtained from conventional supervisory measurements. When it comes to the placement of phasor measurement units, reviews stress that the value of these PMUs lies in their relationship to the observability objectives, the availability of communication links, redundancy and contingency coverage rather than simply in the number of devices [8]. Recent planning studies make a similar point by stating that the installation of PMUs should be coordinated with the requirements of state estimation, protection and control, since a measurement position that is optimal for one application might not offer adequate resilience for another [27]. For the Saudi transmission system, the expansion of PMUs should focus on the corridors with a high renewable energy content, the major interconnections, the critical substations and the stability risks.

Observability is of no use unless the data can achieve the right balance of latency, availability, and integrity. Surveys on communication systems indicate that the requirements of smart grid applications vary greatly: protection and wide-area control need deterministic or near-real-time performance, while asset analytics can allow for greater latency but still require consistent data quality and storage [9]. The transmission architecture must therefore include layered communications, with fibre forming the core of the backbone links and secure wireless systems being able to supplement the fixed networks for remote assets. Redundant routing, accurate time synchronization, and network monitoring are operational necessities, not optional information-technology features, since poor communication can directly affect the reliability of protection and control.

Digital substations act as the link between the primary equipment and the system-wide analytics. By using process-bus and station-bus designs, the need for long copper cables is reduced and it becomes possible to carry out a standardised exchange of information between intelligent electronic devices. The strategic value of these systems lies in the generation of machine-readable, time-stamped data at the point of the substation. With the use of defined data models, the information relating to protection, metering and condition can be reused in operations, maintenance and planning. Yet, interoperability has to be shown in situations involving more than one vendor. Even if an installation is generally in compliance with the standards, it can still place a burden on engineers if the device configuration, naming conventions, firmware management and semantic models are not consistent.

Edge computing deals with another constraint in that it is not necessary for every decision to be sent to a central cloud or control centre. By arranging the smart-grid edge infrastructure so that computing is located nearer to the points of measurement, latency is reduced and the communication burden is lowered, with the local capabilities being maintained even if there are disruptions in the upstream connection [10]. In the case of transmission applications, edge nodes are able to filter out the high-frequency sensor streams, identify anomalies, carry out initial event classification and assist with substation-level applications. Centralised platforms still have a role to play in fleet analytics, model training and in carrying out cross-regional optimisation. A hierarchical approach is suitable: deterministic local functions, regional aggregation, and centralised computation for system-level learning. Figure 1 gives an overview of this architecture, covering the physical assets, the sensing and communication stages, and ending with intelligence and governed action.

The key point is that digitization is not the same as digital transformation. Digital equipment produces data. Transformation happens when you check, add context to, and connect data to decisions. A transmission utility should treat data quality as part of engineering performance. Bad time stamps, inconsistent asset identifiers, and unclear calibration can spread false confidence in analytics. You should set rules for data management, configuration control, and model ownership along with electrical design. The dependability of complex functions depends on having reliable information as a base.

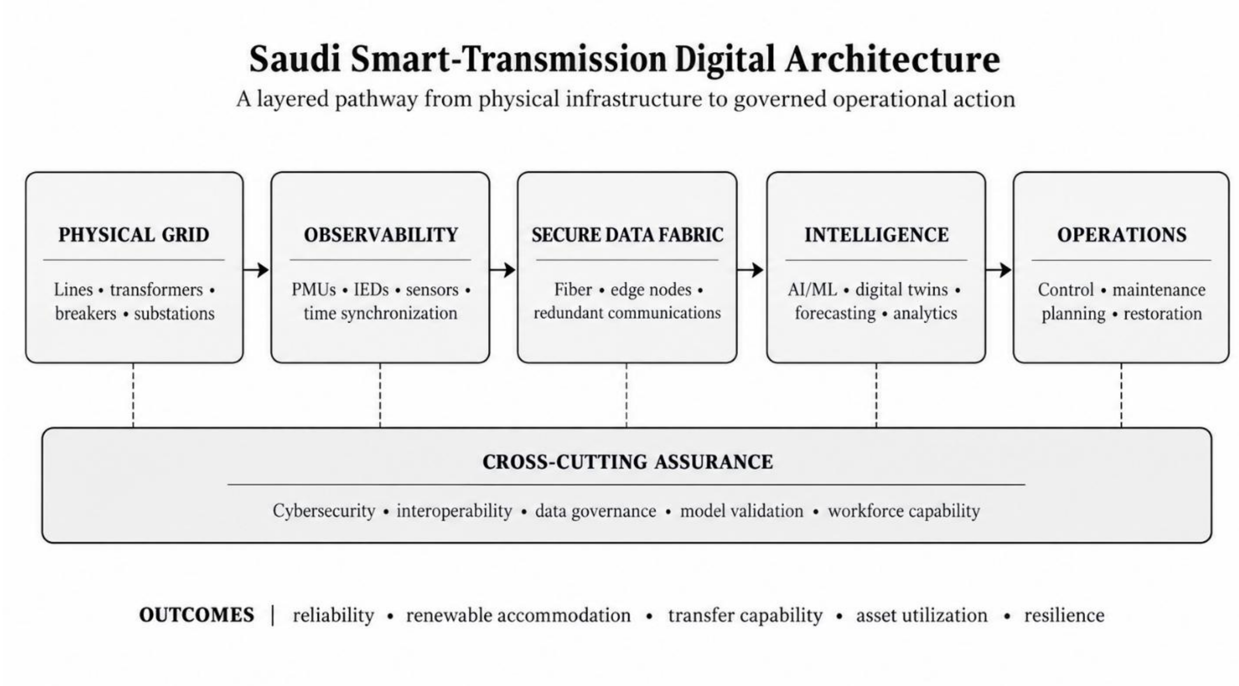

Figure 1. Layered smart-transmission architecture linking physical assets, observability, secure data infrastructure, analytics and governed operations. Source: synthesis developed in this review.

Table 1. Smart grid capability mapping for transmission-level digital transformation.

Capability	Transmission function	Principal value	Implementation caveat
Wide-area measurement	Time-synchronized system visibility	Improves dynamic awareness, event reconstruction and state estimation	Placement, redundancy, timing integrity and communication availability must match use case
Digital substations	Machine-readable protection, control and condition data	Reduces data silos and enables reusable substation information	Multi-vendor engineering, configuration governance and semantic consistency

Capability	Transmission function	Principal value	Implementation caveat
Edge-cloud computing	Hierarchical data processing and analytics	Reduces latency while supporting fleet-scale learning and storage	Clear partition between deterministic local functions and centralized analytics
AI and machine learning	Forecasting, anomaly detection, security assessment and decision support	Extracts patterns from high-dimensional data and supports faster diagnosis	Explainability, distribution shift, validation and human oversight for critical decisions
Digital twins	Dynamic models for assets, corridors or system states	Supports scenario testing, condition assessment and maintenance planning	Model boundaries, uncertainty, topology updates and continuous validation
Energy storage and flexible demand	Fast balancing, reserve, congestion and temporal shifting	Improves renewable accommodation and operational flexibility	Value is location- and control-dependent; response must be observable and dispatchable
Grid-enhancing technologies	Dynamic ratings, flow control and advanced use of existing corridors	Can unlock selected transfer capability faster than major line construction	Benefits are corridor-specific and do not replace structural reinforcement

Capability	**Transmission function**	**Principal value**	**Implementation caveat**
Cyber-resilient architecture	Protection of measurement, communications and control	Preserves integrity and recovery of digitally dependent operations	Security must be engineered across field devices, networks, platforms and vendors

5. Artificial Intelligence, Digital Twins and Asset Intelligence

Although artificial intelligence is frequently shown as the most obvious aspect of a smart grid, its value in this area depends on how the problems are formulated and on the level of maturity of the data. Studies of artificial intelligence in power systems have identified uses in forecasting, fault diagnosis, stability assessment, security evaluation, optimization and planning [11]. Deep reinforcement learning extends this potential to sequential decision problems in which control actions affect the future states of the system [12], and reviews of deep-learning methods indicate an increasing interest in data-driven dispatch and operational support [13]. These techniques are appropriate for dealing with high-dimensional nonlinear problems, but research accuracy does not mean operational reliability.

Analytics for transmission control rooms should be divided according to the level of decision criticality. Examples of low-risk applications are data cleansing, event clustering, maintenance prioritisation and the retrieval of operator information. Medium-risk applications involve probabilistic forecasting, dynamic security assessment and the provision of recommended remedial actions. High-risk applications are those which involve closed-loop control and result in a change to the network state. The higher the level of criticality, the greater the requirements should be for explainability, validation, fail-safe behaviour and independent verification. This step-by-step approach is more defensible than viewing autonomy as a single stage of maturity.

Human supervision is still necessary when dealing with unfamiliar situations and when considering system-wide consequences.

Research into demand-side response also shows that machine learning can be used to improve forecasting and flexibility decisions, even though a great deal of the evidence comes from below the transmission level [14]. The relevance of this in the context of the transmission system is due to the fact that flexible loads and storage become system resources as long as their response can be observed. Although the industrial, desalination and cooling loads in Saudi Arabia may provide flexibility, planners still need validated response models.

Another major area of application is asset intelligence. Failures of high-voltage assets can have wide-ranging effects on the network. Studies of transformer condition monitoring indicate the benefits of combining dissolved gas analysis, thermal data, electrical measurements and diagnostic models in order to detect deterioration before it leads to a catastrophic failure [15]. Through digitalization, periodic assessments are able to be extended towards fleet-level risk management. Data on sensors, loading, maintenance and the environment can be used to prioritise intervention based on condition and consequence rather than on age alone.

Digital twins offer a way of linking these data to engineering models. As noted in reviews of the energy sector, digital twins are described as dynamic virtual representations which combine physical measurements, models and analytical functions in order to aid monitoring, simulation and decision-making [16]. Research into electric digital twin grids is aiming to develop the concept further so as to achieve network-level representations capable of connecting physical assets, communication systems and operational states [17]. Likewise, studies of distribution grids identify condition assessment, real-time monitoring and forecasting as promising applications of the twin approach, while at the same time pointing out the difficulties associated with sensors, model standardisation, data fusion and cybersecurity [18]. Since a large amount of the empirical evidence is focused on distribution systems, further validation is needed for the deployment of transmission systems regarding high-voltage equipment, protection interactions and wide-area dynamic behaviour.

A transmission twin should therefore be designed with a specific purpose in mind rather than merely being a visually impressive copy of all the assets. Thus, a twin based on an asset might be used to estimate the thermal ageing of a transformer; a corridor twin could combine the line ratings, weather conditions, and power flows; and a system twin could be used to test the responses to contingencies when renewable output is changing. In each case there must be a clearly defined model boundary, a stated update frequency, a way of representing uncertainty, and a validation procedure. If these aspects are not properly addressed, the twin will merely speed up the reproduction of inaccurate assumptions rather than lead to better decisions. A particularly promising near-term application in Saudi Arabia is to provide decision support for planning maintenance windows, for the transfer of renewable energy, for assessing equipment stress, and for restoration activities before full integration with control systems.

6. Renewable Integration, Flexibility and Grid-Enhancing Technologies

The integration of renewable energy is an essential part of Saudi Arabia's transmission and transformation efforts. It has been repeatedly shown that smart grids are needed not only since renewable energy is variable, but also because this variability interacts with congestion, reserve requirements, voltage control, system strength and forecasting uncertainty [5-7]. The problem involves both space and time; since high-quality solar and wind resources are often situated far from areas of high demand, corridor planning, dynamic transfer capability and coordinated storage become important elements of a renewable energy strategy.

Energy storage alters the relationship between generation and transmission by shifting energy over time and by offering rapid services. A general review of storage technologies shows that potential applications include frequency regulation, reserve services, peak management, and assistance with the integration of renewables [24]. More recent studies emphasize that the value of storage depends on the technology's characteristics, the control strategy employed, the market or dispatch rules, and its position within the network [25]. A transmission battery should not be judged merely on the basis of its installed power and energy; its value must be evaluated in terms of the amount of curtailment avoided, the relief it provides from congestion, the stability support it gives, the reserve it can provide, its ability to aid in restoration, and the extent to which it delays the need for conventional network reinforcement.

There is another way of increasing the effective transmissibility of electricity through the use of grid-enhancing technologies. Reviews of these technologies mention advanced conductors, dynamic line rating, power-flow control and other methods which can improve the use of existing infrastructure when applied to appropriate constraints [26]. They are important in the context of the rapidly changing generation profile in Saudi Arabia since they might offer faster incremental capacity than new transmission corridors in certain areas. For instance, dynamic line rating replaces the fixed thermal assumptions with operating limits that are based on weather conditions and the state of the conductor. However, these technologies are not general replacements for new lines; their benefits depend on the specific conditions of the corridor and on the ability to safely incorporate them into dispatch operations.

Resource planning studies carried out in Saudi Arabia show how important it is to co-ordinate on a geographical basis. When the solar, wind and hybrid developments are assessed in terms of both space and time, it is found that the resource potential, the distance to existing infrastructure, land limitations and the degree of complementarity differ greatly from one region to another [29]. Another separate case study from Saudi Arabia suggests that integrated planning methods should be used when deploying renewables as part of the Vision 2030 initiative [30]. Since these findings are relevant to the transmission system, the way in which generation sites are decided can either decrease or increase the need for network reinforcement. It follows that the grid should influence the zoning and the procurement of renewables before any projects are selected.

Flexibility must be viewed in the form of a portfolio: forecasting serves to reduce uncertainty; storage enables the movement of energy and the provision of fast services; demand response alters the level of consumption; power-flow controllers redirect the transfers; dynamic ratings show the temporary capacity; and either conventional or emerging synchronous support can meet stability requirements. The digital platform brings these different resources under coordination; flexibility will have only limited value for the system if it is not observable and dispatchable. It therefore follows that transmission digitalization and investments in physical flexibility should be assessed together by means of scenarios that take into account renewable output, contingencies, weather conditions, demand growth and communication failures.

7. Cybersecurity, Interoperability and Digital Governance

The connectivity which allows for smart transmission also increases the cyber-physical attack surface. Cybersecurity assessments reveal the risks present in communication networks, field devices, control systems, data platforms and third-party interfaces [22]. Further research into cyber-physical attacks indicates that false-data injection, denial of service, coordinated manipulation and the compromise of measurement or control channels can influence state estimation and operational decisions [23]. As a result, cyber resilience should be built into the architecture rather than being added afterwards.

A model that can be defended should include segmentation, the principle of least privilege, robust identity management, secure configuration, logging, the ability to detect anomalies, backup communication channels, and well-tested recovery procedures. Security monitoring must take into account the context of the power system in order that unusual network traffic can be understood in relation to electrical events. Just as important is it for utilities to carry out disciplined patching and have firmware governance which does not compromise the reliability of protection. Research oriented towards blockchain suggests the use of tamper-resistant records and decentralised coordination for certain smart-grid transactions [19,20], and combined artificial-intelligence and blockchain approaches have been examined with regard to secure automation [21]. While these methods might be useful in specific applications, they should not be seen as substitutes for fundamental control-system security or for a deterministic operational architecture.

The issue of interoperability is essentially a question of parallel governance. The transmission and transformation process will make use of equipment from a number of different generations and suppliers. By adopting common data models, specifying the interfaces, using standard asset identifiers and implementing version control, the cost of integration can be reduced and the formation of analytical silos avoided. Procurement should therefore look at interoperability over the lifecycle of the system and at data access, not merely at the features of the devices. This represents a significant change in institutional practice: cybersecurity, data governance, protection engineering, telecommunications and operations all have to share responsibility for the design of digital transmission projects.

8. Saudi Vision 2030 Context and a Transmission Transformation Roadmap

The Vision 2030 policy framework is designed so that the electricity infrastructure can contribute to economic diversification, industrial expansion and the establishment of a lower-carbon energy system. A smart-grid analysis that is specific to Saudi conditions states that the deployment of renewable energy, the use of intelligent infrastructure and improved system coordination are mutually reinforcing factors rather than separate initiatives [4]. Similarly, research into the energy transition stresses that technological development, policy-making, human capability and coordination across sectors all need to proceed together [28]. Regarding transmission, advanced platforms will perform poorly if the responsibilities relating to planning, data ownership, cybersecurity and the workforce remain dispersed.

The initial stage of the transformation must involve setting up reliable digital foundations. The key actions here are to finish the inventories of critical assets, ensure that the identifiers for equipment are harmonised, expand the use of time-synchronised measurements, modernise some of the substations, improve the redundancy of communications, and establish common data and cybersecurity requirements. The aim is to achieve dependable visibility of the assets which influence system risk. Priority should be given to critical renewable corridors, large generation interfaces, high-consequence substations and interregional transmission routes. The baseline metrics should include measurement availability, timing quality, communication performance, cyber coverage and data on usable condition.

The second stage must transform the data into integrated operational intelligence, covering such areas as enterprise historians, streaming analytics, condition-based maintenance, better forecasting for renewable energy and demand, wide-area stability applications, and digital twins tailored for specific purposes. Edge computing can be used to carry out local event detection and filtering, with the centralised platforms taking responsibility for fleet analytics and model training. It is important to have governance in place in order to avoid incompatible analytical pipelines, and model management should keep records of the training data, the assumptions, the validation, the software versions, any drift and the authorised use of the models in the case of high-impact models.

Predictive and coordinated control functions should be developed in the third stage. Possible applications in this area are dynamic security assessment, adaptive remedial-action recommendations, dynamic line ratings, coordinated storage dispatch and optimized outage planning. Closed-loop automation should only be introduced in cases where deterministic fallback states, independent protection, and thorough testing have been established. The aim is to decrease the time between a meaningful change in the system and a safe, explainable response. Operator interfaces therefore have to show uncertainty and causal context rather than merely providing algorithmic recommendations.

Because of the nature of Saudi Arabia's physical environment, it is necessary to carry out local validation. The high temperatures, the dust, the coastal salinity in certain areas and the long distances can all have an impact on sensors, communication equipment, cooling systems, insulation and maintenance schedules. The existing literature seldom addresses these factors together on a transmission scale. Pilot programmes should therefore not only check the accuracy of the algorithms but also examine sensor drift, the resilience of communication, the thermal performance of the equipment and the ease of maintenance under actual field conditions. The outcome should be evidence upon which national standards can be based rather than a series of isolated demonstrations.

The need to expand renewable energy capacity has now become more pressing. Studies of Saudi resources show that there is spatial variety in the potential for solar and wind power, and therefore the value of transmission capacity will change as the projects move forward [29,30]. Digital planning tools must connect the different generation scenarios with the capabilities of the corridors, with the location of storage and with contingency performance. This kind of integration can help to improve the timing of investments since traditional reinforcement is still required to meet structural limitations, while digital tools, storage or grid-enhancing technologies can deal with certain bottlenecks. The various options should be compared on the basis of common reliability and lifecycle criteria.

Table 2 shows a step-by-step plan up to the year 2030. In this plan, each technology group is deliberately connected to an operational result and to a governance need in order to avoid the situation where demonstrations do not turn into actual production capabilities. The investment gates must require a tangible improvement in one or more of the following areas: observability, transfer capability, outage risk, restoration, renewable accommodation, asset utilization, cyber resilience or decision quality. Human capability is the last aspect that cuts across all areas. For digital transmission it is necessary to have engineers who are able to work within the fields of power systems, communications, data science and cyber risk, yet who also understand protection principles and the operational consequences. Workforce development should include training, control-room simulations, cyber exercises and joint engineering reviews. Although vendor expertise is useful when implementing the solutions, the fundamental model knowledge, the system data and the authority to make operational decisions should stay with the organisation.

This kind of balance ensures that digital capability continues to exist beyond the duration of contracts and technology cycles.

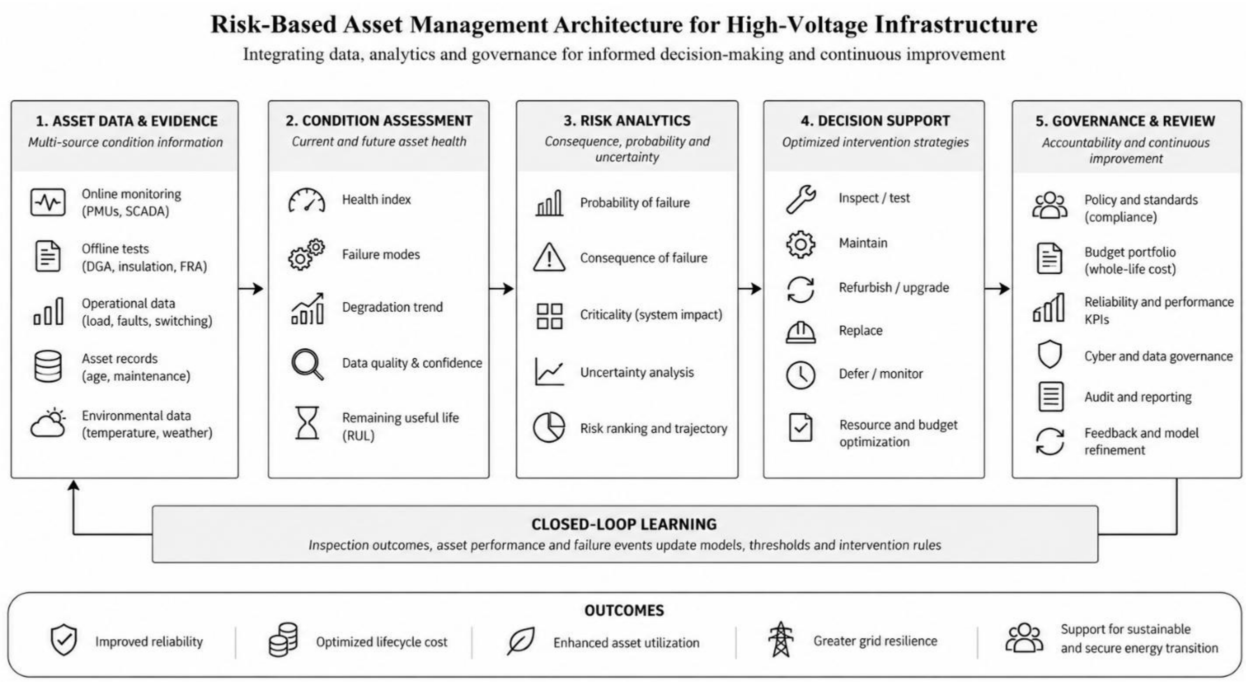

Figure 2. Staged capability pathway from digitization to adaptive transmission operations, with assurance requirements increasing alongside automation. Source: synthesis developed in this review.

Table 2. Proposed Saudi smart-transmission transformation roadmap through 2030.

Stage	Horizon	Priority interventions	Illustrative performance evidence
Foundation: trusted visibility	Now-2026	Critical asset inventory; PMU and IED expansion; digital-substation pilots; redundant communications; common identifiers	Measurement availability; timing quality; critical asset condition-data coverage; cyber-asset inventory

Stage	Horizon	Priority interventions	Illustrative performance evidence
Integration: shared intelligence	2026-2027	Unified data fabric; edge analytics; renewable and demand forecasting; condition-based maintenance; governed model registry	Data-quality exceptions; diagnostic lead time; model validation status; reduction in manual data reconciliation
Prediction: system foresight	2027-2029	Purpose-specific digital twins; dynamic security assessment; dynamic ratings; coordinated storage studies	Forecast error; validated twin accuracy; transfer capability used safely; avoided curtailment or maintenance risk
Adaptive operation	2029-2030	Validated remedial recommendations; coordinated flexible-resource dispatch; selected closed-loop functions with fallback states	Response time; reliability impact; recovery readiness; operator acceptance; verified safe fallback performance

9. Discussion

The available literature reaches a clear conclusion to the effect that the digital transformation of the transmission infrastructure is a systems-engineering issue, not simply an information-technology procurement exercise. The most effective technologies are mutually supportive. PMUs offer synchronized visibility; communications carry out the measurements; edge and central computing transform the data streams into useful information; artificial intelligence identifies patterns; digital twins link the data to engineering models; storage together with grid-enhancing technologies produce controllable flexibility; and cybersecurity ensures the integrity of the whole process. If any of the earlier stages is weak, then the value of the subsequent layers is reduced.

It is for this reason that technology-focused programmes have difficulty in scaling; artificial intelligence is unable to make up for inconsistent asset identifiers or for the absence of measurements. A digital twin will not be able to maintain its credibility if the physical parameters and topology it represents are not kept up to date. Dynamic line ratings will not be able to produce operational value if the dispatch systems do not trust them or use them. Wide-area control cannot be more reliable than its timing and communication infrastructure. Investment should therefore be directed towards an operational capability that has clearly defined requirements regarding data, model, control, security and workforce.

The review also shows an imbalance with regard to the evidence. While technical papers often show the performance of algorithms under controlled data conditions, fewer studies look at organizational adoption, model drift, field maintenance, multi-vendor integration or cyber recovery over the asset's lifecycle. Distribution and microgrid studies are at times employed as evidence of transmission-scale digitalization, even though the effects of a failure and the dynamic interactions can differ greatly. Saudi Arabia's implementation should deal with this gap by means of structured validation.

The transformation route for Vision 2030 should be staged and based on outcomes. Initial investment must ensure that the network is observable and that the data is reliable. Further investment should aim at improving prediction, maintenance and planning. More advanced investment then needs to focus on coordinating flexible resources and at automating certain actions within clearly defined safety constraints. Following this sequence ensures that there are benefits in the short term while at the same time building up the necessary evidence, governance and workforce maturity for more autonomous functions.

Another consequence relates to the ordering of activities beyond the boundaries of organizations. Since transmission planning, operations, asset management, telecommunications and cybersecurity usually assess projects using different performance criteria, even though they rely on the same data infrastructure, a common capability road map could reveal these dependencies before any procurement takes place and thus avoid having to install duplicate sensors, incompatible data stores or separate communication networks. It could also enhance the realization of benefits by designating a specific owner responsible for each operational result after commissioning. Coordination of this kind is important for the Saudi programmes since the fast expansion of the infrastructure can shorten the time available for design and deployment. Standardized interfaces and the use of reusable validation procedures can maintain the pace without compromising engineering assurance or maintainability.

10. Research Gaps and Future Research Agenda

There are four research gaps that should be given priority. Firstly, validation methods for transmission-scale digital twins must be able to quantify uncertainty and stay reliable even when there are changes to the topology, the condition of the equipment and the way the system is operating; comparative studies should examine physics-based, data-driven and hybrid twin designs in relation to actual operational events. Second, artificial intelligence research should go beyond accuracy metrics and focus on explainability, robustness, fail-safe behaviour and gaining the trust of operators. The models should be tested under rare disturbances, missing data, adversarial conditions and distribution shifts rather than merely on historical averages.

Third, integrated experimentation is required in order to achieve cyber-physical resilience. Future research should look at how cyber incidents spread through the stages of measurement, state estimation, protection, dispatch and restoration, including those involving degraded communication methods. Fourth, there is currently a lack of Saudi-specific evidence regarding the combined impact of heat, dust, long communication paths, the concentration of renewable energy and rapid load growth on digital transmission systems. Longitudinal field trials should compare the technical performance, the level of maintenance required and the lifecycle costs across different representative areas.

Another gap in terms of economics relates to the assignment of benefits. Studies should define clear methods for assessing the value of avoided outages, delayed reinforcement, improved transfer capability, less curtailment, reduced maintenance risk and quicker restoration. If such methods are not developed, digital projects might be justified on the basis of general modernisation arguments rather than comparable evidence of investment.

11. Practical, Managerial and Policy Implications

Transmission planners should incorporate digital investments into their network planning studies just as they would incorporate lines, substations, reactive support and storage. Each proposal must indicate the constraint it is intended to address, the data it needs, the failure mode that would occur if the digital function became unavailable, and the fallback operating state. As for asset managers, condition data should be used to inform risk-based decisions regarding maintenance and replacement through common asset models rather than by referring to separate vendor dashboards.

Managers ought to have clearly defined responsibility for data quality, model validation, cybersecurity, software configuration and operational approval. Lifecycle controls similar to those applied to other protection and control measures should apply to high-impact analytics. Procurement should also include requirements relating to interoperability, exportable data, documentation, testing rights and long-term support.

For policymakers and regulators, performance-based indicators are able to promote digital investment without requiring them to specify particular vendors. Appropriate measures should be those relating to critical-asset observability, cyber recovery readiness, renewable curtailment due to network constraints, condition-monitoring coverage and verified improvements in restoration or transfer capability. National standards must be based on experience obtained from the Saudi field and should be coordinated with efforts in the area of workforce development so that the institution's capabilities increase as the complexity of the infrastructure increases.

12. Limitations

The review only includes peer-reviewed literature that was published between 2020 and 2025 as well as a deliberately narrow group of 30 studies which have been verified by their DOIs. As a result, information on rapidly changing vendor platforms and on unpublished utility experience is missing. Although a number of the relevant studies on digital twins, demand response and automation are based at the distribution level, their relevance for transmission was treated with caution rather than taken for granted. The paper presents a conceptual implementation framework and does not provide estimates of the specific costs of projects or of the benefits to the system for the Saudi network. To answer those questions it is necessary to have utility data, topology models and field measurements.

13. Conclusion

Digital transformation will be able to enhance Saudi Arabia's transmission infrastructure only if smart grid technologies are put together to form a reliable operational system. According to the literature examined between 2020 and 2025, synchronized measurement, digital substations, resilient communications, edge-cloud computing, artificial intelligence, digital twins, storage and grid-enhancing technologies can all contribute to improved visibility, flexibility and decision-making regarding assets. However, the advantages of these technologies are subject to interoperable data, cybersecurity, model validation and proper governance.

In the case of Saudi Arabia, it is better to follow a step-by-step approach than to make a sudden shift to autonomy based on technology. The main concern in the short term should be building reliable sensing, communication and data capabilities. The following priority should be integrated analytics, condition intelligence and validated digital twins. Predictive and closed-loop functions should only be expanded once their possible failures, backup states and operational responsibilities have been proven. This order ensures that digital modernisation is in line with Vision 2030 while at the same time safeguarding the reliability requirements of the national transmission system.

All digital projects must be linked to specific measurable outcomes relating to transmission and have to be tested in the conditions under which they will operate in Saudi Arabia. Unless there is clear evidence that improvements can be made in the areas of observability, transfer capability, renewable accommodation, asset risk, or restoration speed and resilience, the extra digital complexity cannot be considered adequate. A smart transmission grid is finally determined not by the number of technologies it connects but by the quality and reliability of the decisions that these technologies allow.

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