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Original Research Article

Climate-Resilient Smart Energy Grid Planning for Extreme Heat and Environmental Conditions in Saudi Arabia

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Abstract: Saudi Arabia is increasing renewable energy generation, electrifying its systems and implementing digital technologies in the grid, all against a backdrop of a climate in which summer temperatures, dust, humidity and other co-occurring environmental stresses simultaneously raise demand and degrade the electricity infrastructure. This study synthesizes the evidence published between 2020 and 2025 to examine how climate-resilient smart-grid planning can help reduce these interconnected risks. A structured integrative review was carried out by selecting a purposeful collection of peer-reviewed studies and official energy and climate reports, with a focus on Saudi Arabia, the Gulf Cooperation Council, arid power systems, and methods of resistance that can be transferred to other contexts. The evidence was analysed along four dimensions: hazard, exposure, vulnerability, and adaptive capacity, and then linked to the areas of generation, transmission, distribution, demand, storage, digital control, and governance. The synthesis reveals that extreme heat is not simply a single issue relating to equipment; it causes cooling peaks at the same time, reduces both generation and network capacity, accelerates thermal ageing, and can occur alongside photovoltaic soiling, constraints on water use, and communication or cyber-physical failures. The most effective approach to planning therefore involves a multi-layered system that incorporates climate-based load forecasting, dynamic asset ratings, heat-resistant equipment, a varied geographical mix of renewable energy sources, storage, demand response, microgrids for critical loads, advanced metering, artificial intelligence, and regional interconnection. The review suggests a planning framework specific to Saudi Arabia that takes into account resilience together with cost and decarbonisation, using measures such as critical-load continuity, energy not served, restoration time, thermal headroom, and forecast error in severe situations. It finds that climate resilience should be integrated into long-term capacity expansion, grid codes, asset standards and operational digital twins, rather than an add-on for emergency management.

Keywords: Saudi Arabia, Climate Resilience, Smart Grid, Renewable Energy, Extreme Heat, Power Grid Resilience, Climate Change.

1. INTRODUCTION

In Saudi Arabia today, electricity planning is reaching a stage at which climate adaptation and the energy transition can no longer be treated as separate issues. The country is moving forward with the deployment of renewable energy, smarter networks, improved efficiency, electrification, and a expanded digital transformation of its infrastructure. The

Springer volume in question views resilience as a problem that derives from interconnected systems and in its chapter on the power system stresses that digitalised grids rich in renewable energy must have the ability to cope with, respond to, and recover from low-probability, high-consequence events. Hayat and Mouchaweh (2025) also point out that the summer conditions in Saudi Arabia can cause temperatures to rise above 50 degrees Celsius, causing higher demand for air conditioning while at the same time reducing the efficiency of certain generation assets and the thermal capacity of power lines. The result is a planning difficulty in which the hazard increases as the amount of available system margin decreases.

The heat issue is made worse by the physical geography of a dry and in part coastal power system. Evidence from Saudi Arabia indicates that photovoltaic soiling is both substantial and dependent on location. Al Garni (2022) recorded the effects of soiling on performance in Saudi Arabia, and AlZahrani (2023) showed the differences in module performance and sensitivity to soiling over a two-year period in the industrial coastal area of Yanbu. Labban and Farahat (2023) found that major dust events affect both the components of solar radiation and the ambient temperature throughout Saudi Arabia, which is why renewable forecasting should regard dust and heat as interacting variables rather than as separate disturbances. Fares *et al*., (2021) do likewise by identifying soiling as a continual challenge across the Gulf that needs mitigation customized to each specific situation.

Studies of regional electricity use show that the pattern of demand in Saudi Arabia is diverse and cannot be properly described by a single national elasticity or growth curve. Mikayilov *et al*., (2020a) identify significant regional variations in the modelling of electricity demand, and Mikayilov *et al*., (2020b) indicate that the factors influencing residential demand are different from region to region. Likewise, industrial demand also has regional features which are important for forecasting and planning (Mikayilov *et al*., 2023). Recent regional projections support the view that it is necessary to model the local developments rather than merely spreading a national forecast throughout the network (Mikayilov and Darandary, 2024).

The issue involved is therefore not simply whether the system has sufficient megawatts during an average year. A climate-resilient smart grid has to be able to sustain essential services when demand, the output of renewable energy, the capabilities of the assets, and the state of communication move outside the range of what has been historically observed. The international literature regarding resilience has as a result moved away from traditional reliability to focus on performance during events, as well as on recovery and modification. Wang *et al*., (2022) define resilience from the points of view of generation, the network, and the load, while Younesi *et al*., (2022) stress the importance of prevention, absorption, adaptation, and recovery within modern power systems. Leddy *et al*., (2023) demonstrate that assessing resilience requires the use of metrics that are related to the consequences of service disruption, not just the expected frequency of outages. These considerations are particularly relevant to Saudi Arabia since the energy transition is taking place in a climate in which extreme heat is itself becoming more likely. Christidis *et al*., (2023) find that human influence is rapidly increasing the chances of temperatures surpassing 50 degrees Celsius in certain areas of the Middle East and the Mediterranean, while Hamed *et al*., (2023) point out significant changes in thermal stress throughout the wider Middle East and North Africa region.

The review is aimed at filling the gap that exists between research on smart grids in Saudi Arabia and research on climate resilience. Rather than reproducing the source document, which mainly concentrates on resilient cities and the power systems of the GCC, it uses the systems approach presented in that document as a methodological basis and then develops a more focused synthesis that is specific to Saudi Arabia and deals with grid planning in climate conditions.

2. Aim, Objectives and Review Questions

This review seeks to combine the body of evidence from 2020 to 2025 as a framework which is specific to Saudi conditions for planning smart electricity grids that are capable of remaining operational under extreme heat, dust, coastal exposure, and a range of combined environmental conditions. The analysis is guided by four objectives. The first is to describe the way in which environmental hazards move through electricity demand, renewable energy output, generation, transmission, distribution, storage, and the digital infrastructure. The second objective is to examine the toughness benefits and limitations of various smart-grid measures such as advanced metering, artificial intelligence, dynamic thermal ratings, demand response, storage, microgrids, digital twins, and regional interconnection. The third entails converting the evidence into climate-adjusted planning metrics and setting out priority stages for investment by Saudi utilities and planners. The fourth is to identify the research gaps that need to be addressed before it will be possible to design high-renewable, highly digital networks based on future rather than previous climate conditions. The relevant questions are: which climate stresses result in the greatest coupled risks; which technologies reduce the consequences rather than just the probability; and how should resilience be incorporated into planning, standards, and operations?

3. REVIEW METHODOLOGY

A structured integrative review was selected because the topic spans electrical engineering, climate science, energy economics, renewable-energy performance, urban resilience, and policy. The review design follows the logic of evidence mapping used in the attached Springer reference (Belaid *et al*., 2025), but replaces its bibliometric topic mapping with a question-driven thematic synthesis focused on Saudi resilience. The review is systematic in its eligibility rules and coding framework, while remaining integrative in how engineering, climate, demand, and policy evidence are combined.

The time frame for the publication search was set between 2020 and 2025 in order to match the scope of the study and to include the period during which the deployment of smart grids in Saudi Arabia, large-scale procurement of renewable energy, the implementation of Vision 2030, and climate-resilience research all sped up. The search terms were grouped into four categories: geography (Saudi Arabia, the Gulf, the GCC, NEOM, arid areas or the Middle East); hazard (extreme heat, high temperature, dust, sand, soiling, humidity, salinity, flood, compound events); system (power system, smart grid, transmission, distribution, transformer, photovoltaic, storage, demand); and response (resilience, adaptation, planning, digitalisation, forecasting, dynamic rating, demand response, microgrid, artificial intelligence). The publisher's and indexing pages were reviewed to confirm the bibliographic information and the persistent identifiers. The final purposive corpus consists of 30 sources, all from the 2020 to 2025 period, and includes peer-reviewed journal articles, chapters from the 2025 Springer volume provided, and high-authority reports from the IEA, IRENA, and IPCC.

Inclusion was based on a direct contribution to at least one of the following five evidence functions: exposure to climate in Saudi Arabia or in the GCC region; electricity demand or the transition in Saudi Arabia; the environmental effects on renewable energy or grid assets; smart-grid as well as resilience technologies; or resilience measurement and planning. Papers were excluded if they had been published before 2020, if a more recent peer-reviewed version was available, if they dealt regarding resilience only in a metaphorical way without any connection to electricity, or if they provided no planning insights which could be applied to a hot-arid system. The review intentionally included a small number of global resilience studies since the Saudi-specific literature has not yet covered all planning methods, especially event-based resilience metrics and system-wide restoration. The purpose of these papers is clearly interpretive rather than serving as evidence of local performance.

The sources were entered into a matrix based on four risk dimensions: hazard, exposure, vulnerability, and adaptive capacity. The hazards consisted of heat, dust, humidity or salinity, storms or flooding, and cyber-physical disruption. Exposure referred to the affected subsystem, for example generation, transmission, distribution, demand, storage or communication. Vulnerability included the means by which performance was lost, such as thermal derating, soiling, corrosion, peak coincidence, forecast error, reduced inverter or sensor capability, and cascading dependency. Adaptive capacity dealt with the planning or operational response. In a second coding phase, the interventions were grouped into seven categories: climate intelligence, asset hardening, network flexibility, storage, demand-side flexibility, digital control, and governance or interconnection. The findings were evaluated in terms of agreement, tension, and evidence gaps rather than being averaged over incompatible metrics.

The evaluation of quality focused on the relevance of the sources, the transparency of the methods, the temporal resolution, the geographic applicability, and whether measured data, validated modelling, or authoritative datasets had been used to support the claims. Context was given to Saudi field measurements such as the Yanbu soiling study when it came to ecological mechanisms, and more general resilience reviews were used to develop planning concepts. Although policy reports offered background on system changes, they were not seen as replacements for evidence on technical performance. The synthesis is therefore best understood as an evidence-based planning framework and a research agenda, not as a probabilistic assessment of future outage risk.

4. Climate and Environmental Stress Pathways in the Saudi Grid

The extreme heat has an effect on both aspects of the power balance. On the side of demand, cooling requirements increase quickly and can become highly synchronized during prolonged periods of hot weather. El Mir (2025) states that cooling is a major factor in causing the peak electricity demand in the GCC region and maintains that achieving heat resilience involves both adaptation and mitigation. As for the supply side, a high ambient temperature can decrease the efficiency of thermal generation, impede heat rejection, reduce the efficiency of photovoltaic conversion, and limit the amount of load that transformers and overhead conductors can carry. Hayat and Mouchaweh (2025) give a clear account of this twofold impact in the case of Saudi Arabia: high temperatures raise air-conditioning demand while at the same time reducing generation efficiency and line capacity. A resilient planning model must therefore employ temperature-adjusted capacity, not nameplate capacity, when evaluating adequacy during extreme events.

Heat also speeds up the ageing process. The insulation of transformers, the joints in cables, power electronics, batteries, and communication equipment are all affected by repeated thermal exposure when this exposure goes beyond normal conditions. Traditional planning usually bases the prediction of asset failure on historical forced-outage rates, assuming that these conditions remain constant. However, this assumption becomes less valid as Zittis *et al.*, (2021) forecast severe heatwaves. The IPCC (2023) states that climate risks rise with every increase in temperature, and Christidis *et al.,* (2023) show that the probability of extreme temperatures of 50 degrees Celsius is increasing across the wider area. Perera *et al.*, (2023) similarly show that climachange and cityban density can lead to new stresses for energy transitions by changing demand and system conditions. For Saudi planners, this gives a reason to move from fixed equipment ratings to thermal-health models which take into account ambient temperature, load history, cooling conditions, age, and maintenance status.

Dust has another, though interacting, effect: it decreases the amount of solsolar radiationat reaches the photovoltaic cells, alters the temperature of the modules, and introduces uncertainty regarding the expected daytime output from renewable sources. Al Garni (2022) has established that soiling has a real impact on photovoltaic performance in Saudi Arabia, and AlZahrani (2023) finds that in Yanbu module technology, the angle of tilt, the season, and the local industrial conditions all affect the losses suffered. Labban and Farahat (2023) show that large dust events can cause changes in both irradiance and ambient temperature at the same time. It is important because on a hot, dusty day solar output is reduced while at the same time cooling demand is high. Fares *et al.*, (2021) examine soiling and countermeasure strategies in the Gulf region and stress that decisions regarding cleaning, coating, tilt, and maintenance should be based on the local dust conditions and water limitations. Hence, planning models which use clear-sky solar profiles without taking into account soiling conditions during specific events will therefore underestimate both the need for balancing and the value of storage.

Because of its coastal exposure, there is an increase in both humidity and the amount of salt deposited, especially with respect to the infrastructure located on the western and eastern coasts. Humidity likewise contribute to ato a greater perceived heat stress and to higher cooling demands. For this reason, different asset specifications should be based on climate zones rather than adopting a single national standard. Procurement with a view to climate resilience therefore needs to establish environmental categories relating to the highest ambient temperature, solar exposure, dust ingress, corrosion, and the redundancy of cooling systems, and then connect these categories to condition monitoring and to planning for replacement.

Compound events represent the biggest analytical shortcoming. A heat wave might occur at the same time as a dust episode, low wind generation, high demand for desalination, or a failure of equipment. Riera *et al.*, (2024) deal with this issue in the context of NEOM by proposing an optimization method which instead keeps extreme weather days rather than eliminating them through time-series reduction. Their method is important since representative-day clustering can cause tail events the kinds of events that lead to investments regarding resilience to be suppressed. Krarti (2024), who is working on creating resilient and carbon-neutral residential communities in the Tabuk area, does likewise show the benefits of combining demand, distributed resources, and resilience at the community level. The takeaway is methodological in that climate-resilient grid planning should intentionally include compound extreme periods in both capacity-expansion and production-cost models, even if these periods make only a small contribution to the total annual energy output.

The Saudi electricity transition can increase or decrease exposure depending on design choices. IRENA (2023) spotlights the region's large renewable potential and the importance of stronger interconnection, while Islam and Ali (2024) emphasize a coordinated Saudi policy framework for the green-energy transition. Ahssein Amran *et al.,* (2020) and AlOtaibi *et al.*, (2020) document the strategic potential in renewable and photovoltaic localization in the Kingdom. Resilience question is therefore not whether renewables are compatible with a stable grid; it is whether deployment is accompanied by geographic diversity, storage, network capacity, firm flexibility, environmental design margins, and accurate forecasting.

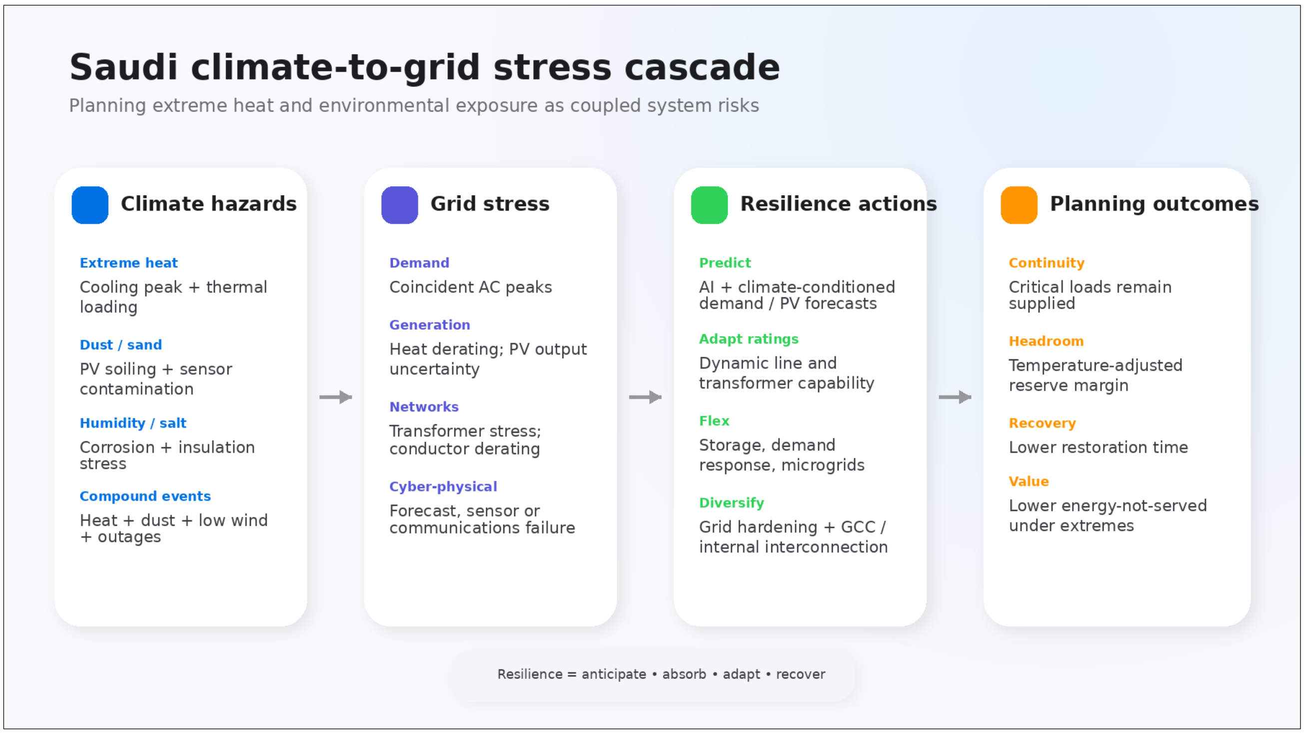

Figure 1: Saudi climate-to-grid stress cascade

Table 1: Climate and environmental stressors relevant to Saudi smart-grid planning

Stressor	Primary mechanism	Exposed grid functions	Planning indicator	Priority design response
Extreme heat	Cooling demand rises while thermal equipment capability can fall.	Generation; transformers; cables; overhead lines; batteries; buildings	Temperature-conditioned peak; thermal headroom; asset hot-spot temperature	Heat-rated equipment; dynamic ratings; cooling redundancy; demand response; storage
Dust and sand	Atmospheric attenuation and deposited soiling reduce PV yield and contaminate exposed equipment.	Solar plants; sensors; insulators; ventilation systems	Soiling ratio; dust optical depth; forecast error; cleaning interval	Dust-aware forecasting; cleaning optimization; coatings; ingress protection; reserve flexibility
Humidity and salinity	Moisture and salt accelerate corrosion and insulation stress in coastal zones.	Substations; connectors; enclosures; insulators; electronics	Corrosion class; leakage current; condition index	Coastal environmental classes; sealed equipment; corrosion-resistant materials; inspection
Storms / flash flooding	Short-duration weather can damage assets, access routes, or substation environments.	Transmission; distribution; substations; communications	Critical assets exposed; restoration access; recovery time	Site protection; drainage; redundant routes; mobile resources; emergency switching
Compound events	Heat, dust, low renewable output, high demand, or asset outage occur together.	Whole cyber-physical power system	Critical-load outage hours; energy not served; minimum reserve	Preserve extreme days in models; geographic diversity; storage; microgrids; coordinated restoration

5. Smart-Grid Planning Architecture for Climate Resilience

The review argues in favour of a multilayered planning approach over relying on a single resilience technology. The first level involves climate intelligence, which means that hourly load and renewable energy forecasts should take into account temperature, humidity, dust levels, cloud cover, wind conditions, and warnings regarding extreme events. Meanwhile, long-term planning should make use of climate-adjusted weather years and specific tail scenarios. As shown by the demand studies carried out in Saudi Arabia, regional modelling does enhance explanatory power (Mikayilov *et al.*, 2020a; Mikayilov and Darandary, 2024). Although artificial intelligence can improve short-term forecasts, it must be trained and subjected to stress testing using rare extreme events rather than being optimised solely for a low average error, since in that case a small annual mean absolute relative error would mask the forecast failures that are important when emergency situations arise.

The second level involves having asset capabilities that take climate factors into account. Static equipment ratings should be enhanced by the use of dynamic or seasonal ratings whenever sensors and verified thermal models are available. Dynamic line rating can show extra capacity that is possible under good conditions and at the same time indicate the need to reduce the load when the conductor temperature or the weather causes the safe loading to drop. Transformer digital twins should combine information on winding temperature, load, ambient heat, dissolved-gas or condition data, and the status of the cooling system in order to estimate the remaining thermal headroom. The IEA (2023) states that the change towards electricity entails the need for grids that are larger, stronger, and smarter; in the case of Saudi Arabia, 'stronger' must involve the use of climate-specific design temperatures and redundancy, while 'smarter' must involve transparent system estimation of the constraints related to heat.

The fourth level relates to flexible supply and storage. Battery energy storage has the ability to shift renewable energy generated during the day into the evening cooling demand peaks, to provide fast frequency response, to support black-start operations where this is technically possible, and to create local power islands around important loads. Eltamaly (2024) shows the benefits of coordinating storage with demand-side management as part of a renewable smart-grid idea in NEOM. When planning storage, it is necessary to take into account battery thermal management and the issue of degradation caused by high ambient temperatures; the nameplate energy does not correspond to the actual energy that can be relied upon during a long heat wave. The resilience portfolio should therefore include resources that have different discharge times and different failure dependencies rather than just striving to maximise installed megawatt-hours.

The fourth element involves granting flexibility in demand. It is possible to reduce or alter cooling peaks without viewing customers as an uncontrolled remainder through the use of smart meters, automated building controls, dynamic tariffs, and utility demand-response schemes. Khan *et al*., (2023) outline the development of Saudi Arabia's smart grid in terms of smart energy, communication, and information infrastructure, whereas Khalid (2024) identifies renewable integration, interoperability, storage, and cybersecurity as the key challenges relating to the smart grid. When considering heat resilience, demand response must be based on thermal comfort and the essential nature of the services in question; curtailment rules must ensure that hospitals, emergency services, vulnerable households, and other essential loads are protected, so that resilience becomes a service priority rather than merely a matter of uniformly reducing load.

The fifth layer is distributed resilience. Although microgrids and distributed energy resources are capable of stopping a disturbance in the transmission system or at a substation from developing into a full failure of vital services, distributed resources by themselves do not automatically result regarding resilience. For example, rooftop photovoltaics that lack grid-forming capability, those with protected islanding, storage, and safe reconnection arrangements can switch off during outages and thus offer no emergency power. Planning standards should therefore differentiate between ordinary distributed generation and those distributed systems which have resilience capabilities, including specific requirements relating to protection, communication, black-start behaviour, minimum autonomy, and testing.

The sixth level relates to network and regional diversity. By allowing the exchange of energy and reserves during unusual demand or supply situations, interconnection among the GCC countries adds a further element of diversity. Hayat and Mouchaweh (2025) specifically regard the GCC power exchange as a means of enhancing resilience, on the basis of better forecasting of extreme weather, line capacity, and renewable generation. IRENA (2023) also sees regional interconnection as an asset that can help accommodate a higher proportion of renewable energy. It must, however, not be considered as guaranteeing an emergency supply: it is possible for neighbouring systems to be affected by the same regional heat event. Firm import capacity must therefore be evaluated using weather and demand scenarios that are correlated, not those that rely on average transfer availability.

The seventh layer concerns cyber-physical resilience as well as governance. Although digitalization improves observability and control it also expands the attack surface and results in a dependence on communication systems. In order to achieve resilience the architecture must include segmented networks, redundant means of communication, secure device identity, backup power for the control systems, manual fallback procedures, and regular recovery drills. According to Khalid (2024) cybersecurity and interoperability are identified as the two major issues relating to the smart grid, and the attached Springer chapter stresses the interaction between the physical and cyber domains. Yet a technically advanced grid can still be vulnerable if institutional coordination breaks down during a compound event.

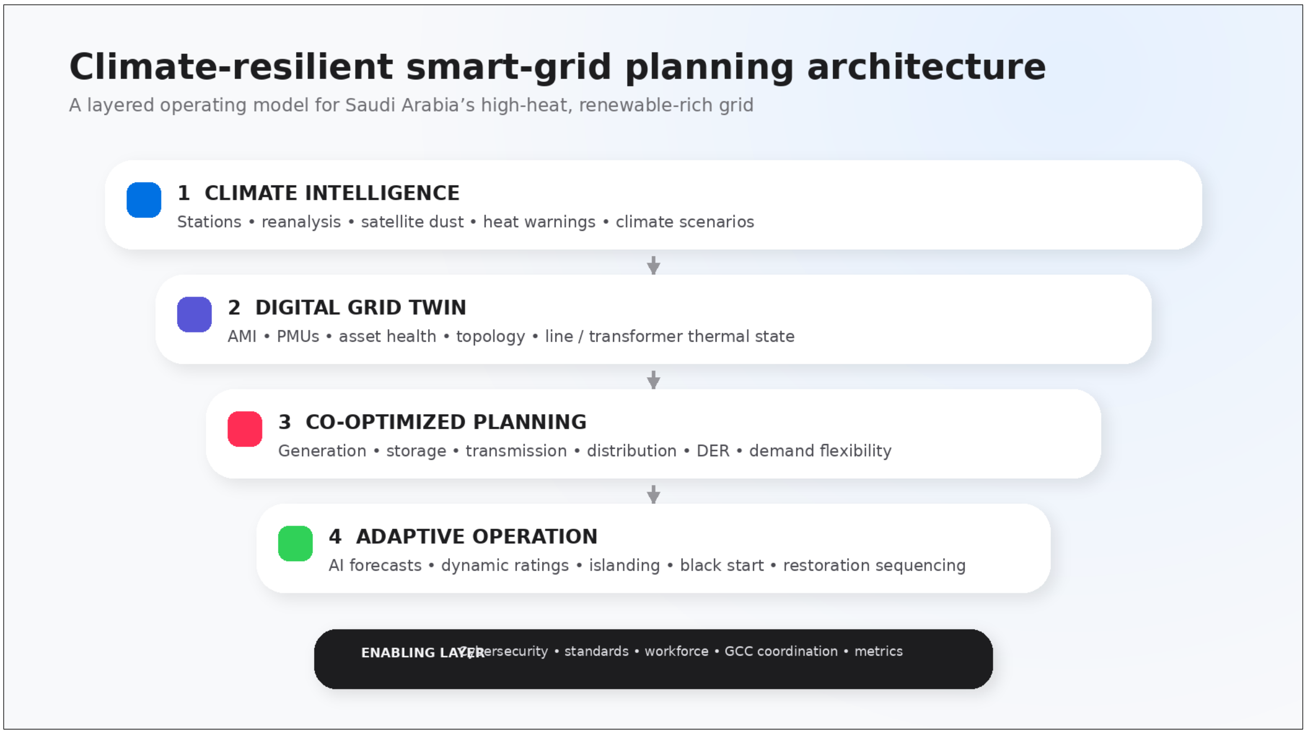

Figure 2: Layered climate-resilient smart-grid planning architecture

Table 2: Priority smart-grid measures and their climate-resilience value

Measure	Resilience function	Heat / environment role	Key limitation	Suggested Saudi priority
Climate-aware AI forecasting	Anticipation	Forecasts cooling peaks, PV output, and constraint timing using weather and dust inputs.	Rare-event training data and model drift.	Very high
Dynamic thermal ratings	Adaptive capacity	Estimates real line or transformer capability instead of relying only on static ratings.	Requires validated sensors, models, and operating rules.	High on constrained corridors
Battery and long-duration storage	Absorption / recovery	Supplies evening cooling peaks, fast reserves, and critical loads after disturbance.	Thermal management, degradation, duration, and cost.	Very high where critical-load or congestion value is strong
Demand response / smart buildings	Flexibility	Reduces coincident AC peaks through pre-cooling, cycling, and load shifting.	Comfort, equity, customer participation, and control integration.	Very high in metropolitan load centers
Resilience-capable microgrids	Continuity	Islands hospitals, water assets, data services, or remote loads.	Protection, grid-forming controls, storage duration, testing.	High for critical service clusters
Grid hardening and environmental specifications	Prevention	Improves tolerance to heat, dust ingress, corrosion, and flooding.	Capital intensive if applied without risk differentiation.	Targeted high priority
Internal and GCC interconnection	Diversity / sharing	Accesses geographically diverse generation and reserves during local stress.	Regional heat can correlate demand and reduce surplus simultaneously.	High, but stress-test import firmness

6. Resilience Metrics and Investment Logic

Planning that is resilient to climate change needs to use indicators which reward continuity and the ability to recover, not just annual reliability. Although traditional indices are still useful for assessing normal performance, they may give too little weight to rare events that have serious social effects. Leddy *et al.,* (2023) look at methods for measuring and valuing resilience inside the power sector and affirm the importance of linking technical performance with its consequences. For Saudi Arabia's planning purposes, a practical scorecard should take into account the amount of energy that is not served during specified extreme scenarios, the number of hours for which critical loads are out, the time it takes to restore defined service levels, the minimum operating reserve when adjusted for temperature conditions, storage autonomy, the success rate of islanding, communication availability, and the forecast error that occurs during the hottest or dustiest percentiles. These metrics should be assessed together with cost, emissions, and renewable curtailment in the expansion models.

The objective in this case should be to achieve the lowest cost after taking resilience into account, rather than first seeking the lowest cost and then carrying out a qualitative assessment regarding resilience. For instance, a transmission upgrade might seem costly when average dispatch levels are taken into account, but it becomes important when it offers an alternative route during a period of derating caused by heat. A battery might generate only a small amount of annual arbitrage income but can still have high option value if it makes certain that a hospital's microgrid is kept powered during the first few hours of a disturbance. Dynamic ratings can delay capital expenditure in one area while at the same time showing that hardening is needed in another. The issue is not to perfectly quantify every possible outcome; it is to make sure that planning algorithms do not give zero value to the avoidance of a catastrophic loss of service simply because the frequency of such an event in the past has been low. Both Wang *et al*., (2022) and Younesi *et al*., (2022) support a multi-stage approach regarding resilience that takes into account the stages of preparation, absorption, adaptation, and recovery.

The different levels of demand in various regions should be directly taken into account in these metrics. As Mikayilov *et al*., (2023) have shown, industrial electricity demand has regional features, and Darandary *et al*., (2024) have demonstrated that electricity-price reforms have an effect on regional fuel use and emissions. It follows that an effective resilience portfolio for an industrial coastal area should focus on corrosion-resistant equipment, process-load coordination, and redundant feeders; for an inland metropolitan area it should prioritise cooling-peak management and transformer thermal margin; and for a remote development longer-duration storage and islandable microgrids would be required. Although a national resilience standard can specify the desired outcomes, the least-cost way of achieving them should still vary from one region to another.

7. DISCUSSION: PRIORITIES FOR SAUDI ARABIA

The evidence points to five planning priorities in the near term. Firstly, climate data ought to be incorporated as an engineering input and network studies should regularly examine future heat thresholds, the effects of dust on photovoltaic performance, humidity or coastal derating, and days when multiple events occur, rather than depending on a single historical typical meteorological year. As Riera *et al*., (2024) have shown, extreme days must be included in the optimisation process, and Christidis *et al*., (2023) have demonstrated that historical upper-temperature limits can no longer be regarded as safe assumptions. Second, utilities should establish a national heat-vulnerability register which connects each important asset with its design temperature, the observed thermal margin, age, cooling arrangement, level of environmental exposure, the extent of condition-monitoring coverage, and the consequences of a failure. This would ensure that the measures taken to harden systems are based on evidence rather than being applied in a uniform manner.

Third, smart-grid investments should be assessed in terms of their resilience function. Simply counting technology is an inadequate way of measuring the intelligence of the grid. Both Khan *et al*., (2023) and Khalid (2024) stress that the smart grid is an integrated energy-information-communication system. The climate-resilience extension then relates to the types of decisions the system is able to make before, during, and after an extreme event.

Fourthly, the deployment of renewable energy should be combined with environmental performance guarantees and flexibility. The localisation strategies of Saudi Arabia offer the chance to specify heat-resistant inverters, heat-resistant electronics, suitable coatings, robotic or water-efficient cleaning methods, dust sensors, and corrosion-resistant balance-of-system components. AlOtaibi *et al*., (2020) examine the localisation of the photovoltaic industry, whereas Al Garni (2022) and AlZahrani (2023) give local evidence showing that environmental conditions have a material effect on the output delivered. Policy should recognise and reward reliable capacity during periods of stress, not just the annual energy output. This also supports geographic and technological diversity: solar power, wind power, flexible gas use during the transition period, storage systems, interconnection, and responsive demand should be seen as complementary resilience resources rather than as technologies that exclude one another.

Fifth, resilience must be combined with decarbonization rather than be used to delay it. Islam and Ali (2024) describe the Saudi energy transition as a coordinated policy issue, and Ahssein Amran *et al*., (2020) point out a large renewable potential in line with Vision 2030. IRENA (2023) additionally underscores the rapid potential for renewable energy throughout the GCC. The real problem lies in the order in which actions are taken. If fossil fuel-based capacity is retired or reduced before sufficient flexibility, storage, network strengthening, and operational functions have been put in place, this can result in unnecessary risk; on the other hand, keeping inflexible, high-emission capacity for an indefinite period can lead to transition lock-in. It is therefore necessary to reduce risk, not just phase out technologies: each increase in variable renewable capacity should be matched by an adequate amount of balancing, grid, storage, demand, and toughness capabilities in order to ensure the desired service outcomes are maintained.

This summary also points out the connection between water and energy. When there is extreme heat, the need for cooling goes up and so does the demand for water, whereas desalination itself requires a lot of electricity. El Mir (2025) regards this interaction as a major concern for durability in the GCC. In Saudi Arabia, coordinated planning should make use of flexible pumping and water storage as demand-side resources so long as it is operationally safe, and critical desalination requirements need a secure supply and should be given priority for restoration. The same principle holds true in the case of electric mobility and digitally managed cities: the introduction of new electrified loads brings about opportunities for flexibility but additionally increases the impact of outages. Resilience planning must therefore be carried out as an integral part of infrastructure-system planning, not just within the electricity utility.

8. Research Gaps and Future Agenda

The initial research gap consists in the lack of publicly available, asset-specific heat fragility curves for power equipment in Saudi Arabia. Since such curves are not available, analysts may accurately depict heat demand yet have to make only a rough approximation of supply-side vulnerability. To address this, field data from various climate zones should be anonymised and combined in order to estimate failure thresholds and recovery times; the outcome would then aid probabilistic resilience studies and enable the development of climate-adjusted maintenance policies.

Secondly, datasets relating to compound events are not well developed. Future research needs to create multivariate event libraries that maintain the joint extremes in temperature, humidity, dust optical depth, wind, solar output, demand, equipment outages, and water-system load. Hamed *et al*., (2023) and Christidis *et al*., (2023) have provided climate evidence indicating that thermal extremes are getting worse, and Labban and Farahat (2023) have shown that dust events affect a number of meteorological variables. Such data should be used in chronological production-cost and expansion models rather than in separate sensitivity analyses. Research ought to compare the solutions chosen on ordinary representative days with those chosen when extreme clusters are specifically kept, just as Riera *et al*., (2024) have demonstrated the approach.

Thirdly, in order to test the strength of artificial intelligence it is necessary to evaluate its performance under rare conditions. Since most forecasting models are trained on a large number of normal observations, rare events such as heat waves, dust storms, device failures and changes to the network topology occur only infrequently. Future research needs to include in its reporting the error rates associated with tail events, calibration, explainability, and graceful degradation, as well as merely the average prediction accuracy. Combined models which combine physical principles with machine learning might prove to be more reliable when it comes to dynamic ratings and estimating asset health. Cybersecurity testing should also be incorporated since if the data is compromised or becomes unavailable it can turn an automated resilience feature into a vulnerability. The criterion for success should be safe decision support in situations of uncertainty, not the achievement of maximum predictive complexity.

Fourthly, economic valuation must take into account consequences that are specific to Saudi Arabia. The cost of failing to provide energy is not the same for all households or for different sectors such as desalination, petrochemicals, hospitals, data centres, transport, and emergency services. It is therefore necessary for a national resilience valuation framework to incorporate the interruption costs specific to each sector together with factors relating to equity and the significance of critical services. Although Leddy *et al*., (2023) have provided a useful basis for this, local calibration is still essential. Furthermore, research should look into who bears the cost of redundant capacity, microgrids, hardened assets, and storage when the benefits spread beyond the owner of the asset to the wider urban and economic systems.

In the end, demonstration projects ought to progress from trials of individual components to comprehensive resilience exercises. An appropriate pilot programme should integrate a climate-aware digital twin, dynamic ratings, grid-scale storage, automated demand response, a critical-load microgrid, and secure communications within a single area that experiences high temperatures. Performance must be assessed during controlled stress tests and during actual summer peaks by using the toughness criteria suggested in this review. These pilots would transform the present body of literature—from a set of promising technologies—into practical evidence regarding interoperability, human decision processes, restoration, and institutional coordination.

9. CONCLUSION

In Saudi Arabia smart-grid planning aimed at improving resilience should start with this simple idea: the most difficult periods are those in which climatic conditions raise the demand for electricity while at the same time worsening the resources employed to meet that demand. Due to extreme heat there will be a synchronised demand for cooling, the thermal margins will be reduced, the ageing of equipment will be accelerated and dust-related losses for photovoltaic systems or other environmental stresses will occur at the same time. Although digitalisation and the incorporation of renewable energy sources can strengthen the system, this is only possible if observability, flexibility, physical hardening, storage, demand response, cybersecurity and the ability to restore services are all part of a single overall design.

The evidence for the period 2020 to 2025 indicates that a planning approach can be both practical and in line with the Kingdom's energy transition. Utilities should prepare demand and renewable energy forecasts on the basis of climate conditions, keep the records of extreme and compounded days in their planning data sets, introduce dynamic asset capability where it has been validated, strengthen assets in accordance with the local environmental categories, deploy storage and demand flexibility in relation to key constraints, tell the difference between normal distributed generation and microgrids that are capable of providing resilience, and make use of both internal and GCC interconnections as diversity resources. The efficacy of these measures should be assessed using event-based indicators such as energy not served, critical-load continuity, restoration time, and thermal headroom, not just annual reliability.

The main contribution of this review is a shift in planning logic. Resilience is not an additional technology category and not a reserve margin added after an optimised plan is complete. It is a criterion that changes forecasts, ratings, scenarios, investment values, operating rules, and governance. Embedding that criterion now would allow Saudi Arabia to expand a cleaner and more digital electricity system without carrying previous climate assumptions into infrastructure expected to operate for decades. The strongest research priority is therefore to convert Saudi field data on heat, dust, assets, demand, and outages into validated climate-risk models that can guide investment before extreme conditions become the new normal.

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