Global Academic Journal of Economics and Business

Available online at https://www.gajrc.com
DOI: https://doi.org/10.36348/gajeb.2026.v08i04.042

ISSN: 2706-9001 (P)
ISSN: 2707-2584 (O)

Original Research Article

Net Zero Ready MEP Strategies for Tourism Infrastructure in Saudi Arabia: Advancing Sustainable Regional Development under Vision 2030

Saquib Syed[1]*
[1]Independent Researcher

***Corresponding Author**
Saquib Syed
Independent Researcher

Article History
Received: 14.06.2026
Accepted: 06.08.2026
Published: 17.08.2026

Abstract: Saudi Arabia's tourism expansion is creating a new class of hotels, resorts, cultural destinations, transport interfaces and mixed-use visitor districts whose mechanical, electrical and plumbing systems will determine long-term energy demand, water security, operational resilience and carbon exposure. This review develops a context-specific framework for making such infrastructure net-zero ready under Vision 2030. A structured integrative review of literature and official evidence published from 2020 to 2025 was undertaken across building performance, district energy, renewable integration, microgrids, water efficiency, digital engineering and reliability-centred operations. The synthesis distinguishes net-zero readiness from an immediate claim of net-zero operation: readiness is defined as the technical and institutional capacity to reduce demand, electrify end uses, connect to low-carbon energy, flex loads, verify performance and avoid carbon lock-in throughout the asset life cycle. Evidence indicates that cooling-led load reduction, high-efficiency chillers, low-temperature networks, thermal storage, solar generation, intelligent controls and robust commissioning should be designed as one system rather than procured as isolated packages. For tourism assets, the framework also requires occupancy-responsive operation, peak-season resilience, water-energy coordination and service continuity during extreme heat or visitor surges. Digital twins and building information models can strengthen option appraisal and operational feedback, but their value depends on interoperable data, competent teams and contractual access to measured performance. The paper proposes a six-layer strategy, a staged delivery roadmap and an indicator set linking carbon, energy, water, reliability and regional value. It concludes that net-zero-ready MEP infrastructure can advance sustainable regional development when performance requirements are embedded in master planning, procurement, commissioning and long-term facilities management, rather than added after architectural design has been fixed.

Keywords: Net-Zero Readiness, Mechanical, Electrical and Plumbing Systems, Tourism Infrastructure, Saudi Arabia, District Cooling, Energy Efficiency, Utility Resilience, Vision 2030.

Citation: Syed, S. (2026). Net Zero Ready MEP Strategies for Tourism Infrastructure in Saudi Arabia: Advancing Sustainable Regional Development under Vision 2030; *Glob Acad J Econ Buss, 8*(4), 993-1003. https://doi.org/10.36348/gajeb.2026.v08i04.042

1. INTRODUCTION

Tourism has become a strategic engine of economic diversification in Saudi Arabia, with investment extending beyond conventional hotels into coastal resorts, mountain destinations, heritage districts, entertainment venues, airports, mobility hubs and entire visitor-oriented regions. Vision 2030 links this expansion to employment, private investment, cultural activation and more balanced regional growth [2-7]. Yet every new destination also commits the Kingdom to decades of electricity and water demand. In a hot-arid environment, mechanical, electrical and plumbing (MEP) systems are not secondary building services: they are the operating infrastructure that controls thermal comfort, indoor air quality, potable-water delivery, sanitation, fire safety, lighting, vertical transport, communications and business continuity. Decisions made during concept design can therefore either preserve future decarbonisation options or lock projects into oversized, inflexible and carbon-intensive systems.

The net-zero challenge is particularly demanding for tourism assets. Occupancy varies by day, season and event; guestrooms and public spaces require distinct comfort and ventilation regimes; kitchens, laundries, pools, spas and landscape irrigation create intensive thermal and water loads; and guest expectations discourage visible service compromise. Coastal humidity, dust, high ambient temperatures and remote sites can reduce equipment efficiency and accelerate degradation. At destination scale, simultaneous cooling demand can stress local grids, while water production, pumping and treatment add an indirect electrical burden. Saudi net-zero policy must therefore be translated into engineering strategies that address energy, water and resilience together rather than treating carbon as a single annual accounting exercise [4-9].

Recent literature provides strong but fragmented knowledge. Net-zero building studies explain demand reduction, electrification and renewable supply [10-30], district energy research examines low-temperature networks, thermal storage and flexible operation [12-16], digital engineering studies demonstrate opportunities for simulation, life-cycle analysis and operational twins [1-29], and maintenance research shows that reliability and availability can be optimised when failure behaviour is considered explicitly [28]. However, tourism infrastructure in Saudi Arabia combines these domains under conditions that are not fully represented by generic office or residential models. The central problem is consequently not the absence of technologies, but the absence of an integrated decision logic that identifies which measures must be fixed early, which can be phased, how performance should be verified, and how MEP investment can create wider regional value.

This paper addresses that problem through a review focused on net-zero readiness. The term is used deliberately. A project may not operate at net zero on its first day because the grid, renewable capacity, storage economics or destination occupancy profile may still be evolving. It can nevertheless be designed so that future decarbonisation does not require disruptive replacement of major plant, risers, substations or utility corridors. Conversely, a project marketed as efficient may remain unready if its electrical capacity, controls, metering, refrigerants, hydraulic temperatures or contractual arrangements prevent later electrification and clean-energy integration. Net-zero readiness thus combines present efficiency with future adaptability, measurable operation and avoidance of technological lock-in.

2. Aim, Objectives and Review Questions

The aim of this review is to formulate an evidence-based MEP strategy for Saudi tourism infrastructure that can progress towards net-zero operation while supporting resilient and inclusive regional development. Four objectives guide the analysis: first, to identify the MEP interventions with the strongest relevance to hot-arid tourism assets; second, to explain how building, district and utility decisions should be sequenced to prevent carbon lock-in; third, to integrate energy, water, digital operation and reliability within one performance framework; and fourth, to translate the technical synthesis into procurement, commissioning and regional-capacity priorities. The review asks three questions: Which MEP measures most effectively establish net-zero readiness? How should those measures be adapted to Saudi climatic and tourism operating conditions? Which governance and measurement arrangements are necessary to convert design intent into verified life-cycle performance?

3. REVIEW METHODOLOGY

A structured integrative review was selected because the research question spans engineering design, operations, infrastructure planning and policy rather than a single intervention or homogeneous outcome. Searches covered publications dated January 2020 to December 2025 in Scopus, Web of Science Core Collection, ScienceDirect and IEEE Xplore, supplemented by official Saudi strategy material and internationally recognised energy reports. Search strings combined terms for net zero, low carbon, MEP, HVAC, district cooling, thermal storage, microgrids, building information modelling, digital twins, water efficiency and predictive maintenance with tourism, hospitality, resorts, hot-arid climates, Saudi Arabia and the Gulf. Backward and forward citation checks were used to identify closely related studies when their methods or findings were directly relevant to the synthesis.

Sources were included when they were peer reviewed or institutionally authoritative, published within the stated period, written in English, and offered a clear contribution to MEP demand reduction, energy conversion, renewable supply, flexibility, water management, operational verification or reliability. Studies were also required to have a transferable connection to tourism buildings, district infrastructure or hot-climate operation. Duplicate records, purely promotional project descriptions, papers without an identifiable method, and studies that discussed sustainability without a building-services mechanism were excluded. Thirty sources were retained for the final evidence base. This intentionally bounded set allowed detailed comparison while meeting the review's emphasis on recent, decision-relevant evidence.

The analysis used a mechanism-to-outcome matrix. Each source was coded against six strategy domains: demand and load reduction; efficient thermal and electrical conversion; clean supply and storage; water and circular utilities; digital design and operations; and reliability, governance and delivery. Reported benefits were mapped to measurable outcomes such as annual energy use intensity, peak electrical demand, cooling-system coefficient of performance, renewable fraction, potable-water intensity, unplanned downtime and operational carbon. Evidence was treated as high strength when results were measured or modelled with transparent boundaries and baselines, medium strength when methods were clear but context transfer was required, and contextual when the source primarily established policy direction or market conditions.

The synthesis did not aggregate effect sizes because the studies differed substantially in climate, building type, system boundary and operating assumptions. Instead, convergent findings, implementation dependencies and areas of disagreement were compared qualitatively. Particular attention was paid to the difference between projected and realised performance. Simulation can identify technically feasible options, but operational claims were credited only when commissioning, metering or monitored data were discussed. The approach also distinguished building-level measures from district and regional interventions, since a high-performing hotel cannot compensate for an inefficient utility network, while a low-carbon district system cannot deliver its potential if connected buildings retain excessive loads. Table 1 summarises the review design and evidence rules.

Table 1: Review design and evidence interpretation

Review element	Specification	Analytical purpose
Period and sources	2020-2025; peer-reviewed databases plus authoritative Saudi and international reports	Prioritise recent evidence and policy relevance
Scope	MEP demand, thermal systems, electricity, renewables, storage, water, digital operation and reliability	Capture building, district and utility interdependencies
Inclusion rule	Transparent method; measurable mechanism; relevance to tourism, districts or hot-arid operation	Retain decision-useful evidence
Synthesis unit	Mechanism-to-outcome relationship	Avoid treating technology adoption as proof of performance
Evidence interpretation	High, medium or contextual strength	Separate measured outcomes from transferable or policy evidence
Primary outcomes	Energy, peak demand, carbon, water, reliability, comfort and regional capability	Support multi-dimensional net-zero readiness

4. Saudi Tourism Infrastructure as an MEP Decarbonisation Context

Saudi Arabia's net-zero pathway is shaped by rapid demand growth, a cooling-dominated load profile and an electricity system in transition. National studies indicate that efficiency is economically important because reducing final demand lowers both fuel use and the scale of renewable generation required for decarbonisation [4-6]. Tourism projects intensify this issue because many destinations are being constructed simultaneously and may reach peak use during periods of high ambient temperature. The regional-development benefit of tourism can therefore be weakened if new assets create large permanent utility subsidies, require overbuilt networks or suffer reliability problems that damage destination reputation.

Climate changes the technical ranking of measures. High dry-bulb temperatures reduce air-cooled equipment performance, while humidity near the Red Sea increases latent cooling and dehumidification loads. Dust and salt exposure affect heat exchangers, photovoltaic output and outdoor electrical equipment. Remote developments may have constrained grid connections, limited maintenance capability and costly water supply. The design response should not be a blanket increase in plant size. Excessive safety factors produce low-load cycling, poor part-load efficiency and capital waste. More reliable outcomes come from calibrated weather files, diversified occupancy profiles, explicit degradation allowances, N+1 strategies for genuinely critical services, and modular capacity that can follow staged tourism demand.

Tourism also creates unusual operating diversity. A resort may include guestrooms, restaurants, retail, conference halls, wellness facilities, staff housing, back-of-house logistics and outdoor attractions. These zones have different schedules and sensible-to-latent load ratios. Their simultaneous peaks are often lower than the sum of individual design peaks, creating an opportunity for shared thermal infrastructure and diversity-based sizing. At regional scale, clusters of hotels and attractions can support district cooling, central water treatment, reclaimed-water networks and common energy centres. Such systems can improve efficiency and resilience, but only when governance, tariffs, connection standards and expansion phases are defined before individual plots adopt incompatible solutions.

The concept of readiness is therefore spatial as well as technical. Buildings need efficient envelopes, low-temperature distribution, heat-recovery opportunities, adequate electrical pathways and granular metering. Districts need reserved utility corridors, scalable energy centres, thermal storage sites, renewable zones and interoperable control architecture. Regions need skills, service companies, spare-parts strategies and transparent performance requirements. The resulting framework must connect room-level comfort control to national decarbonisation without assuming that one technology is universally optimal.

5. Net-Zero-Ready MEP Strategy Synthesis

The reviewed evidence supports a six-layer hierarchy. Demand should first be reduced and reshaped; remaining loads should be served by highly efficient MEP systems; thermal and electrical end uses should be compatible with progressively cleaner supply; storage and controls should provide flexibility; water and material flows should be treated as energy issues; and performance should be maintained through digital verification and reliability-centred operation. The layers are interdependent. Installing photovoltaics before correcting excessive cooling demand enlarges capital cost and leaves operational weaknesses intact, while efficient chillers without metering or commissioning may never achieve their calculated performance. Figure 1 presents the integrated architecture.

5.1 Demand Reduction and Load Shaping

The most robust net-zero strategy is to avoid unnecessary load before selecting plant. For tourism buildings, this requires coordinated envelope, shading, glazing, infiltration, lighting and ventilation decisions. Architectural identity should be preserved, but façade concepts must be tested against orientation-specific solar gain and realistic internal schedules. High-performance glazing alone is insufficient if large unshaded areas create radiant discomfort that drives lower thermostat settings. External shading, vestibules, airtightness, cool roofs and reduced lighting power can lower both annual energy and peak chiller capacity. Early energy models should use room-type schedules rather than one average hotel profile, and should test occupancy uncertainty, climate extremes and phased opening.

Ventilation and humidity control deserve equal attention. Dedicated outdoor-air systems can separate latent treatment from zone sensible cooling, enabling better humidity control and avoiding the reheating penalties that occur when one air system attempts to satisfy both functions. Demand-controlled ventilation is suitable for variable-occupancy spaces such as ballrooms, restaurants and meeting rooms, provided minimum health requirements and sensor quality are protected. Heat recovery should be evaluated against pressure drop, contamination risk and local humidity. Guestroom controls can use door, occupancy and booking data to relax temperature and airflow during vacancy while restoring comfort before arrival. These measures are operational, not merely technological: poorly calibrated sensors or aggressive setbacks can create complaints and manual overrides that erase savings.

Load shaping complements reduction. Chilled-water thermal storage can shift cooling production away from electrical peaks, improve chiller loading and reduce required grid capacity. Domestic hot-water production, laundry cycles, pool heating and electric-vehicle charging can also be scheduled when renewable generation or spare network capacity is available. In a destination with diverse facilities, aggregation creates flexibility that individual buildings cannot provide. The design target should therefore include peak kilowatts and ramp rates, not only annual kilowatt-hours. Flexible demand is particularly valuable where tourism expansion precedes full grid reinforcement or where microgrids must maintain critical services during disturbances.

5.2 High-Efficiency HVAC and District Thermal Systems

Cooling is the principal MEP decarbonisation opportunity. Selection should be based on annual system performance across load and weather bins rather than a single full-load equipment rating. Variable-speed chillers, optimised condenser-water temperatures, low-pressure-drop distribution, efficient pumps and correctly selected cooling towers can materially improve performance. Plant sequences should minimise the combined power of chillers, pumps and heat rejection, because optimising one component in isolation can increase total system energy. Metering at plant and major load branches is necessary to calculate system coefficient of performance and identify fouling, control drift or hydraulic imbalance.

District cooling can be attractive for dense tourism clusters because it exploits load diversity, centralises specialist operation and enables large thermal stores. Recent reviews of fourth- and fifth-generation networks emphasise lower distribution temperatures, bidirectional exchange, storage and integrated control [12-16]. In Saudi applications, the optimal architecture may differ from European low-temperature heating networks, but the underlying principles remain useful: minimise temperature lift, reduce distribution losses, recover useful heat where practical, and preserve modularity. Hotels can provide simultaneous cooling and hot-water demand, creating opportunities for heat recovery from condenser water or heat-pump systems. The business case depends on pipe routing, connection density, tariff design and phased occupancy; a central plant that runs far below design load for years can underperform a modular solution.

Net-zero readiness requires refrigerant strategy as well as electrical efficiency. Equipment should minimise leakage, support lower-global-warming-potential refrigerants where technically and safely appropriate, and allow future servicing without dependence on obsolete fluids. Refrigerant charge, leak detection and recovery procedures belong in the carbon plan because direct emissions can be significant. Resilience should be achieved through maintainable redundancy, hydraulic isolation, spare capacity sequencing and emergency operating modes, not through chronic oversizing. Critical zones such as data rooms, medical facilities, food storage and life-safety spaces require explicit continuity targets, whereas guestrooms may tolerate controlled temperature drift during short events.

5.3 Electrification, Renewable Energy, Microgrids and Storage

As electricity supply becomes less carbon intensive, electrification increases the ability of tourism assets to decarbonise. Electric heat pumps can replace combustion for domestic hot water and low-temperature heating, particularly when waste heat from cooling is available. Kitchen and laundry equipment should be assessed for electric alternatives, heat recovery and process efficiency. Electrical master plans must reserve transformer, switchgear and cable capacity for future electrification, charging infrastructure and storage, while avoiding premature installation of oversized equipment. Space, access, protection philosophy and harmonic management should be fixed early because later retrofits can be disruptive.

Solar photovoltaic generation is well aligned with daytime cooling, but roof area is often constrained by architectural features, plant, shading and guest amenities. Car parks, service yards, canopies and adjacent land can expand the usable area. Generation estimates must account for dust, temperature derating, cleaning water, degradation and curtailment. Renewable design should be based on hourly coincidence with load rather than annual energy matching alone. Batteries can support peak shaving, power quality, renewable firming and short-duration continuity; however, chilled-water storage may provide lower-cost flexibility for cooling-dominated loads. Hybrid optimisation should compare electrical and thermal storage on equivalent service outcomes rather than treating batteries as the default solution.

Remote or weak-grid destinations may benefit from microgrids combining grid supply, photovoltaics, storage and controllable loads [19]. Their value lies in coordinated operation: critical circuits, black-start requirements, islanding logic and restoration sequences must be defined with the utility and emergency plans. Diesel generation may remain necessary for life safety or exceptional outages, but readiness means reducing runtime and designing pathways toward lower-carbon backup as technologies mature. The microgrid controller should expose data and operating rules to the destination's energy-management platform so that resilience is not achieved at the expense of inefficient routine operation.

5.4 Water-Energy Integration and Circular Utilities

Water efficiency is inseparable from net-zero MEP planning because desalination, treatment, pumping, heating and wastewater management consume energy. Tourism facilities have substantial loads from guestrooms, kitchens, laundries, pools, spas and landscaping. Low-flow fixtures, pressure management, leak detection, efficient laundry processes and submetering reduce both water demand and associated energy. Hot-water recirculation should be hydraulically balanced and controlled to maintain hygiene while limiting heat loss. Solar or heat-pump water heating should be integrated with storage and recovered heat, with careful attention to legionella control, peak draw and seasonal occupancy.

At district scale, treated wastewater and greywater can support irrigation, cooling-tower make-up or suitable non-potable uses when quality, health regulation and salinity are managed. Condensate from air-handling units can be significant in humid coastal locations and should be captured where the treatment and distribution burden is justified. Cooling-tower cycles of concentration, blowdown recovery and chemical treatment need optimisation because water-saving measures that cause scaling can reduce chiller efficiency. A combined water-energy dashboard is therefore more useful than separate utility reports: it can reveal whether a reduction in potable water has increased pumping, treatment or chemical demand elsewhere.

5.5 Digital Engineering, Commissioning and Predictive Operation

Building information modelling and analytical tools can connect geometry, plant selection, embodied carbon, energy simulation, water calculations and maintainability. The attached reference study shows that Gulf adoption of sustainability-oriented BIM functions is influenced strongly by regulation, client requirements, awareness and organisational readiness [1]. Energy and waste functions are relatively established, while renewable integration and digital twins are more recent. This implies that requiring a model is not enough. Employers' information requirements should specify data needed for load validation, asset handover, control points, metering, maintenance and future carbon reporting. Open exchange formats and clear ownership reduce dependence on one vendor.

Operational digital twins can compare measured performance with expected behaviour, diagnose faults and test control changes [20]. Their practical value depends on a reliable sensor hierarchy, naming conventions, time synchronisation and contextual data such as occupancy and weather. A small set of trustworthy points is preferable to thousands of unvalidated signals. Analytics should target decisions: chiller sequencing, simultaneous heating and cooling, stuck dampers, leaking valves, abnormal night loads, filter pressure and water loss. Alarm rationalisation is essential because operators will ignore systems that generate excessive low-value alerts.

Commissioning is the bridge between design and operation. It should begin with the owner's project requirements, continue through design reviews and factory testing, and conclude with seasonal verification after occupancy. Functional tests must examine part-load, failure and recovery modes rather than demonstrating only that equipment starts. Metering should be commissioned as carefully as plant, with calibration, data-quality checks and traceable boundaries. Soft landings, operator training and post-occupancy tuning are especially important for tourism assets because the first year often includes phased openings and unstable occupancy. Performance contracts can retain design and controls expertise through this period and link payments to verified outcomes rather than document completion.

5.6 Reliability, Maintainability and Service Continuity

Net-zero systems must be dependable enough to protect the guest experience. Complex controls or highly integrated plants can create new failure modes if local capability, spare parts and override procedures are neglected. Reliability-centred maintenance research demonstrates the value of linking preventive tasks to failure behaviour, cost and availability rather than applying fixed intervals to every component [28]. Tourism projects should classify assets by consequence: life safety, business continuity, guest comfort, resource efficiency and environmental risk. Criticality then determines redundancy, condition monitoring, spares and response times.

Predictive maintenance can use vibration, temperature, electrical and control data to identify degradation before failure. Nevertheless, the programme should begin with accurate asset registers, failure codes and maintenance feedback. Heat exchanger fouling, refrigerant leakage, sensor drift and poor water treatment can quietly increase energy long before equipment fails. Maintenance indicators should therefore combine availability with energy deviation. A plant that remains operational but uses twenty per cent more electricity is not performing successfully. Remote sites also require maintainability-by-design: safe access, lifting routes, isolation points, component standardisation and local stock can be more valuable than sophisticated analytics unsupported by field capability.

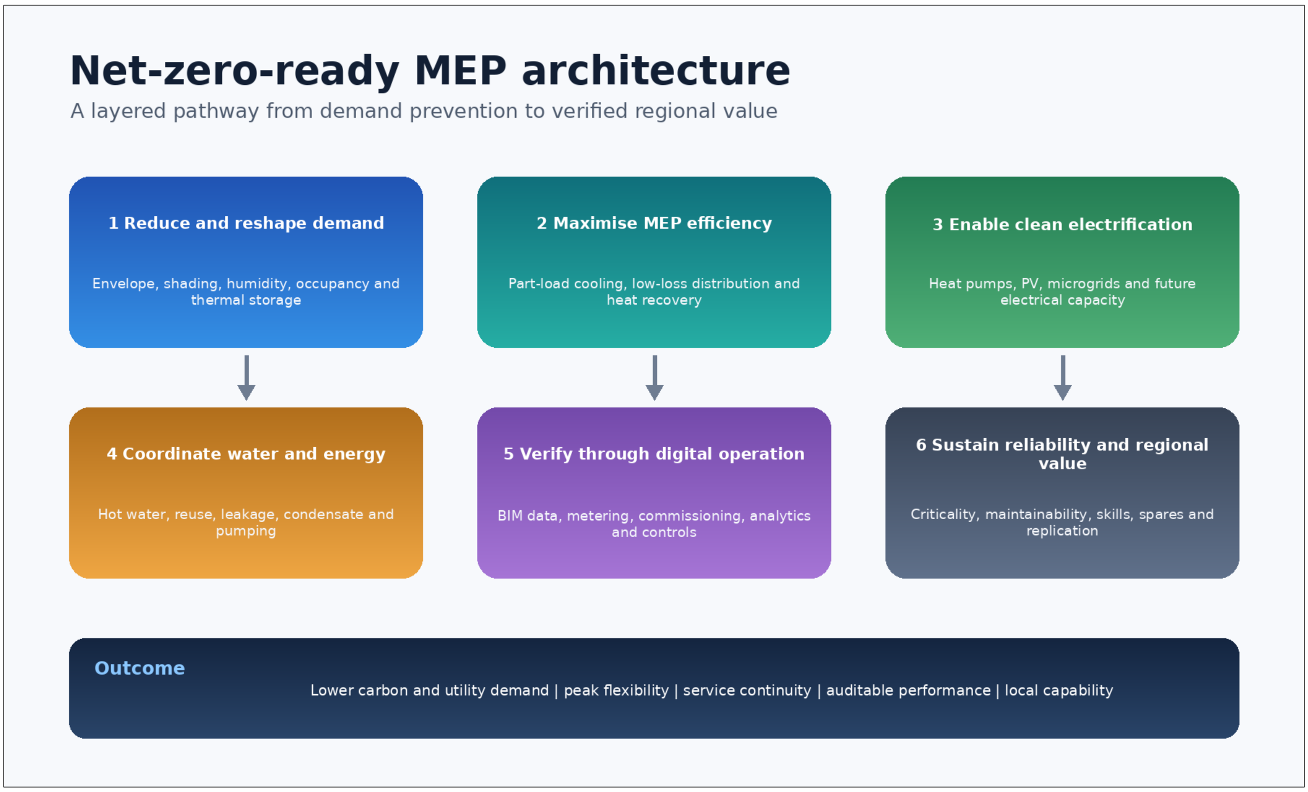

Figure 1: Integrated architecture for net-zero-ready tourism MEP systems

6. Integrated Delivery Framework and Regional Development

The strategy can be implemented through six decision gates. Gate one establishes the carbon, energy, water and resilience baseline at master-plan level, including utility constraints and development phasing. Gate two sets passive-design and load budgets for each plot before architectural concepts are frozen. Gate three selects building and district MEP architectures through whole-life comparison, including future grid decarbonisation, refrigerants, maintenance and expansion. Gate four protects interfaces for renewable generation, storage, electrification, metering and data exchange. Gate five verifies construction and commissioning against measurable requirements. Gate six uses operational data to tune assets, update regional benchmarks and trigger planned upgrades. Figure 2 illustrates this progression.

Procurement must preserve the logic across packages. Employer requirements should define maximum energy-use intensity, peak demand, plant efficiency, water intensity, renewable readiness, critical-load autonomy, refrigerant leakage, meter coverage and data availability. Design-build or public-private partnership contracts should distinguish calculated targets, commissioned capability and achieved operational performance. The distinction prevents forecast savings from being reported as completed outcomes and enables fair accountability when occupancy or weather differs from assumptions. Tariffs for district cooling, reclaimed water or microgrids should reward efficiency and flexibility rather than encourage consumption.

Net-zero-ready MEP investment can contribute to regional development beyond the asset boundary. Modular energy centres, maintenance workshops, controls integration, water laboratories and commissioning services create specialised employment. Standardised systems across a tourism region can support local spare-parts inventories and training programmes. Renewable and storage projects can strengthen utility infrastructure that also serves communities, while reclaimed-water networks can reduce pressure on potable supplies. These benefits are not automatic: local value should be specified through competency requirements, supplier-development plans and knowledge transfer, without compromising safety or technical quality.

Table 2 translates the synthesis into a strategy matrix. It emphasises that no single measure defines readiness. The relevant question is whether the combined system can reduce and flex demand, accept cleaner supply, maintain service under stress, and produce data that demonstrate performance. A destination that achieves these conditions can decarbonise progressively as national electricity, technology and tourism demand evolve.

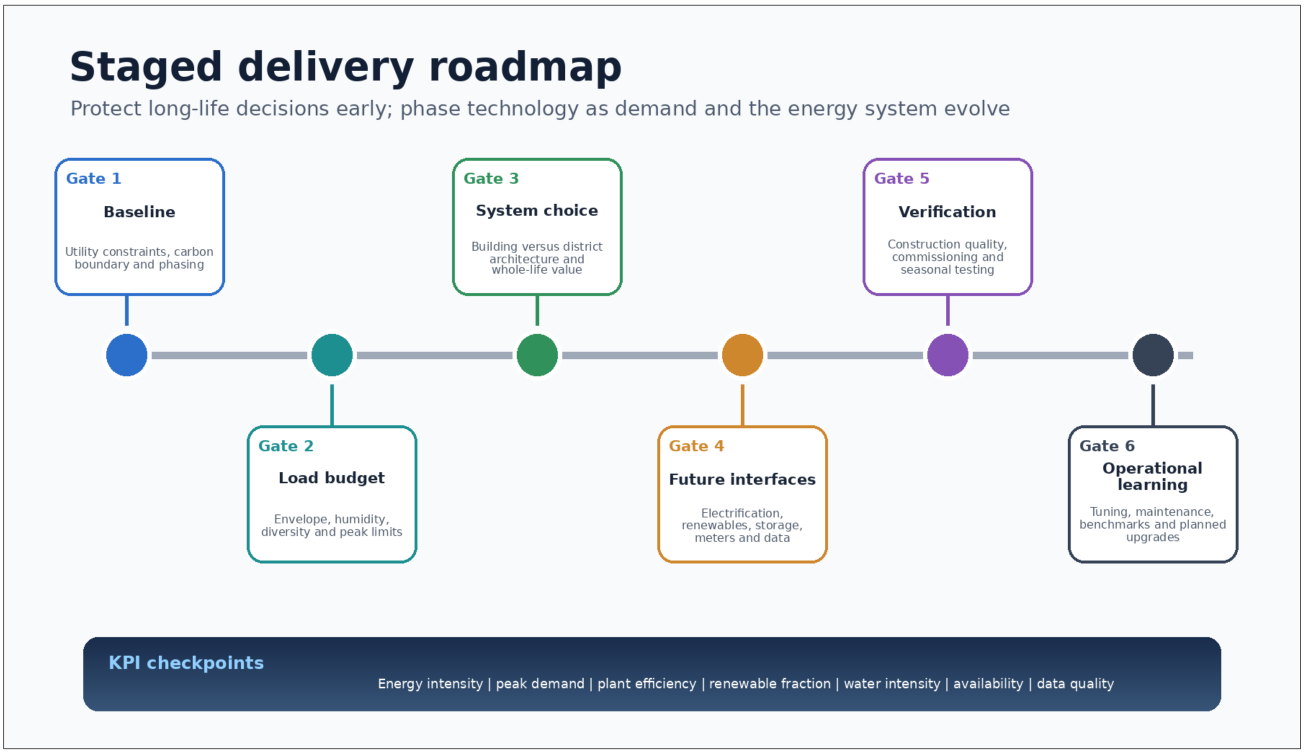

Figure 2: Staged delivery and verification roadmap for destination-scale implementation

Table 2: Net-zero-ready MEP strategy matrix for tourism infrastructure

Strategy domain	Priority MEP decisions	Key indicators	Tourism application	Principal delivery risk
Demand and load	Envelope coordination, humidity control, occupancy logic, thermal storage	$kWh/m^2 \cdot yr$; W/m^2 peak; load factor	Guestrooms, event spaces, restaurants	Generic schedules and oversized plant
Efficient cooling	Part-load chiller selection, hydraulic optimisation, heat recovery, district cooling	System COP; kW/RT; distribution loss	Resort clusters and mixed-use destinations	Central plant built ahead of demand
Clean electricity	Electrification pathways, PV, batteries, microgrid interfaces	Renewable fraction; peak kW; critical autonomy	Remote sites, car parks, service zones	Annual matching without hourly analysis
Water-energy nexus	Submetering, efficient hot water, reclaimed water, condensate and leak control	L/guest-night; kWh/m^3; loss rate	Laundry, pools, spas and landscaping	Water savings that impair plant efficiency
Digital performance	BIM data requirements, interoperable controls, commissioning and analytics	Meter coverage; fault closure; energy deviation	Portfolio-wide performance management	Poor data quality and vendor lock-in
Reliability and value	Criticality analysis, maintainability, spares, training and local capability	Availability; MTTR; local service share	Life safety and guest-service continuity	Complex systems without operator capacity

7. DISCUSSION

The evidence suggests that the most important design choice is integration, not technology novelty. Mature measures such as shading, efficient chillers, variable-speed pumping, thermal storage, heat recovery, submetering and commissioning remain central. Their impact increases when they are coordinated through realistic load models and district planning. By contrast, high-profile technologies can underperform when selected without reference to operating profiles, maintenance or utility constraints. Net-zero readiness therefore requires engineering discipline: explicit boundaries, hourly analysis, scenario testing, verified controls and whole-life decisions.

Several tensions remain. First, resilience can increase capital and embodied impacts through redundancy, yet insufficient resilience can cause service failure and emergency energy use. Criticality-based design offers a better balance than uniform redundancy. Second, district systems can deliver diversity and professional operation, but they can also lock customers into inefficient tariffs or central technologies. Transparent performance standards, modular expansion and connection rights are necessary. Third, digitalisation can improve verification, although it introduces cybersecurity, interoperability and skills risks. The appropriate response is governed data architecture and operator-centred design, not rejection of digital tools.

The review also exposes an evidence gap. Many studies model technical potential, while fewer report multi-year performance of tourism assets in hot-arid regions. Published evidence often lacks consistent treatment of occupancy, weather normalisation, water-energy interactions, refrigerant emissions and service quality. Saudi destination developers are well placed to close this gap because large portfolios can use common meters, naming standards and reporting templates. Anonymised benchmark datasets would allow researchers and operators to distinguish design shortcomings from operational drift and would reduce repeated mistakes across projects.

This performance logic also supports comparison across destinations because common definitions allow owners to benchmark similar assets without ignoring climate, occupancy, service level, system boundary or development phase. Comparable information improves investment decisions, strengthens operator learning and helps authorities identify where infrastructure standards require revision. It also enables regional programmes to reward verified improvement rather than installed technology, encouraging practical innovation while retaining accountability for comfort, safety, resilience and long-term utility performance outcomes.

A further implication concerns timing. Net-zero readiness should not wait for a fully decarbonised grid. Load reduction, low-temperature distribution, electric pathways, flexible controls and meter architecture have long asset lives and must be decided now. Some renewable or storage capacity can be phased as economics and occupancy mature, provided land, electrical interfaces and control protocols are protected. This staged approach reduces stranded capital while preserving ambition. It is particularly suitable for regional tourism programmes where plots open over several years and demand forecasts contain unavoidable uncertainty.

8. CONCLUSIONS

Saudi tourism infrastructure can support sustainable regional development only if MEP systems are treated as strategic, long-life infrastructure. This review defines net-zero readiness as the capacity to minimise demand, operate efficiently, electrify end uses, connect to cleaner energy, provide flexibility, conserve water, maintain service and verify outcomes over time. The strongest strategy is a hierarchy beginning with climate-responsive load reduction, followed by efficient cooling and pumping, district integration where density and phasing justify it, renewable generation and appropriate storage, water-energy coordination, and digitally enabled commissioning and maintenance.

For developers and public authorities, the decisive actions occur before construction. Master plans should reserve energy and water corridors, establish plot-level performance budgets and evaluate diversity. Procurement should specify measured outcomes, interoperable data and seasonal commissioning. Facilities-management capability, spare-parts planning and reliability targets should be designed with the plant rather than added at handover. Performance should be tracked through a concise set of carbon, energy, peak-demand, water, refrigerant, availability and comfort indicators, with transparent boundaries and normalisation.

The framework does not assume that every destination must use identical technology or achieve immediate annual net-zero balance. Coastal resorts, mountain developments, heritage districts and urban hotels have different loads and utility options. They should, however, avoid irreversible choices that prevent future decarbonisation. By combining present efficiency with planned adaptability, Saudi tourism projects can lower operating risk, strengthen local technical capacity and create infrastructure that remains compatible with national climate and development goals through 2030 and beyond.

REFERENCES

1. El Hajj, C.I.; Martínez Montes, G. Examining Green Building Practices: The Influence on Building Information Modeling Function Diffusion. Sustainability 2025, 17, 3843. https://doi.org/10.3390/su17093843.
2. Kingdom of Saudi Arabia. Vision 2030 Annual Report 2024. Riyadh, 2025.
3. Ministry of Tourism, Saudi Arabia. Hospitality Investor: Invest in Saudi Arabia's Tourism Sector - An Exceptional Opportunity. Riyadh, 2024.
4. Al-Sinan, M.A.; Bubshait, A.A.; Alamri, F. Saudi Arabia's Journey toward Net-Zero Emissions: Progress and Challenges. Energies 2023, 16, 978. https://doi.org/10.3390/en16020978.
5. Al-Gahtani, S.F. Saudi Arabia's Journey toward a Renewable Future. Energies 2024, 17, 2444. https://doi.org/10.3390/en17112444.

6. Belaïd, F.; Massié, C. The Viability of Energy Efficiency in Facilitating Saudi Arabia's Journey toward Net-Zero Emissions. Energy Economics 2023, 124, 106765. https://doi.org/10.1016/j.eneco.2023.106765.
7. Ahmed, I.; Mehrez, K.; Socci, C.; Deriu, S.; Mathkur, N.M.; Casasr, I.P. Disaggregated Effect of Construction Investments on the Saudi Economy: A Dynamic Computable General Equilibrium Model of Saudi Arabia. Financial Innovation 2024, 10, 1-17. https://doi.org/10.1186/s40854-023-00530-1.
8. Arenhart, R.S.; Martins, T.; Ueda, R.M.; Souza, A.M.; Zanini, R.R. Energy Use and Its Contributors in Hotel Buildings: A Systematic Review and Meta-Analysis. PLoS ONE 2024, 19, e0309745. https://doi.org/10.1371/journal.pone.0309745.
9. Almulhim, A.I.; Al-Saidi, M. Circular Economy and the Resource Nexus: Realignment and Progress towards Sustainable Development in Saudi Arabia. Environmental Development 2023, 46, 100851. https://doi.org/10.1016/j.envdev.2023.100851.
10. Ahmed, A.; Ge, T.; Peng, J.; Yan, W.-C.; Tee, B.T.; You, S. Assessment of the Renewable Energy Generation towards Net-Zero Energy Buildings: A Review. Energy and Buildings 2022, 256, 111755. https://doi.org/10.1016/j.enbuild.2021.111755.
11. Hawks, M.A.; Cho, S. Review and Analysis of Current Solutions and Trends for Zero Energy Building Thermal Systems. Renewable and Sustainable Energy Reviews 2024, 189, 114028. https://doi.org/10.1016/j.rser.2023.114028.
12. Gjoka, K.; Rismanchi, B.; Crawford, R.H. Fifth-Generation District Heating and Cooling Systems: A Review of Recent Advancements and Implementation Barriers. Renewable and Sustainable Energy Reviews 2023, 171, 112997. https://doi.org/10.1016/j.rser.2022.112997.
13. Yao, S.; Wu, J.; Qadrdan, M. A State-of-the-Art Analysis and Perspectives on the Fourth- and Fifth-Generation District Heating and Cooling Systems. Renewable and Sustainable Energy Reviews 2024, 202, 114729. https://doi.org/10.1016/j.rser.2024.114729.
14. Guo, Y.; Wang, S.; Wang, J.; Zhang, T.; Ma, Z.; Jiang, S. Key District Heating Technologies for Building Energy Flexibility: A Review. Renewable and Sustainable Energy Reviews 2024, 189, 114017. https://doi.org/10.1016/j.rser.2023.114017.
15. Dang, L.M.; Nguyen, L.Q.; Nam, J.; Nguyen, T.N.; Lee, S.; Song, H.-K.; Moon, H. Fifth Generation District Heating and Cooling: A Comprehensive Survey. Energy Reports 2024, 11, 1723-1741. https://doi.org/10.1016/j.egyr.2024.01.037.
16. Buffa, S.; Fouladfar, M.H.; Franchini, G.; Gabarre, I.L.; Chicote, M.A. Advanced Control and Fault Detection Strategies for District Heating and Cooling Systems - A Review. Applied Sciences 2021, 11, 455. https://doi.org/10.3390/app11010455.
17. Wu, W.; Skye, H.M. Residential Net-Zero Energy Buildings: Review and Perspective. Renewable and Sustainable Energy Reviews 2021, 142, 110859.
18. Heendeniya, C.B.; Sumper, A.; Eicker, U. The Multi-Energy System Co-Planning of Nearly Zero-Energy Districts: Status Quo and Future Research Potential. Applied Energy 2020, 267, 114953. https://doi.org/10.1016/j.apenergy.2020.114953.
19. Abdelsattar, M.; Ismeil, M.A.; Aly, M.M.; Abu-Elwfa, S.S. Energy Management of Microgrid with Renewable Energy Sources: A Case Study in Hurghada, Egypt. IEEE Access 2024, 12, 19500-19509. https://doi.org/10.1109/ACCESS.2024.3356556.
20. Cespedes-Cubides, A.S.; Jradi, M. A Review of Building Digital Twins to Improve Energy Efficiency in the Building Operational Stage. Energy Informatics 2024, 7, 11. https://doi.org/10.1186/s42162-024-00313-7.
21. Alvur, E.; Anaç, M.; Mert Cüce, A.P.; Cüce, E. The Potential and Challenges of BIM in Enhancing Energy Efficiency in Existing Buildings: A Comprehensive Review. Sustainable and Clean Buildings 2024, 1, 42-65.
22. Mehraban, M.H.; Alnaser, A.A.; Sepasgozar, S.M.E. Building Information Modeling and AI Algorithms for Optimizing Energy Performance in Hot Climates: A Comparative Study of Riyadh and Dubai. Buildings 2024, 14, 2748. https://doi.org/10.3390/buildings14092748.
23. Jamoussi, B.; Abu-Rizaiza, A.; Al-Haij, A. Sustainable Building Standards, Codes and Certification Systems: The Status Quo and Future Directions in Saudi Arabia. Sustainability 2022, 14, 10314. https://doi.org/10.3390/su141610314.
24. Hasanain, F.A.; Nawari, N.O. BIM-Based Model for Sustainable Built Environment in Saudi Arabia. Frontiers in Built Environment 2022, 8, 950484. https://doi.org/10.3389/fbuil.2022.950484.
25. Batista, L.T.; Franco, J.R.Q.; Fakury, R.H.; Porto, M.F.; Alves, L.V.R.; Kohlmann, G.S. BIM-IoT-FM Integration: Strategy for Implementation of Sustainable Water Management in Buildings. Smart and Sustainable Built Environment 2023, 13, 1096-1116.
26. Zhang, Y.; Jiang, X.; Cui, C.; Skitmore, M. BIM-Based Approach for the Integrated Assessment of Life Cycle Carbon Emission Intensity and Life Cycle Costs. Building and Environment 2022, 226, 109691.

https://doi.org/10.1016/j.buildenv.2022.109691.
27. Cascone, S. Digital Technologies and Sustainability Assessment: A Critical Review on the Integration Methods between BIM and LEED. Sustainability 2023, 15, 5548. https://doi.org/10.3390/su15065548.
28. Liu, Y.; Tang, Y.; Wang, P.; Song, X.; Wen, M. Reliability-Centered Preventive Maintenance Optimization for a Single-Component Mechanical Equipment. Symmetry 2024, 16, 16. https://doi.org/10.3390/sym16010016.
29. Schamne, A.N.; Nagalli, A.; Soeiro, A.A.V.; Martins, J.P.d.S.P. BIM in Construction Waste Management: A Conceptual Model Based on the Industry Foundation Classes Standard. Automation in Construction 2024, 159, 105283. https://doi.org/10.1016/j.autcon.2024.105283.
30. International Renewable Energy Agency. Renewable Energy and Jobs: Annual Review 2023. Abu Dhabi, 2023.

