Energy Efficiency Improvement Through Sustainable MEP Systems and Electrical Infrastructure Integration in Saudi Mega Projects

Abstract

Saudi mega projects combine large cooling loads, complex service networks and increasingly sophisticated electrical infrastructures. Their energy outcomes depend not only on the efficiency of individual equipment but also on coordination between mechanical, electrical and plumbing (MEP) systems, controls, distribution architecture and operational governance. This critical review examines research published during 2020–2025 to establish how integrated design and operation can improve efficiency while maintaining indoor environmental quality and electrical reliability. Evidence is organised around cooling plant selection, hydraulic and ventilation design, demand flexibility, onsite generation, digital coordination, fault management and wholelife carbon. A transparent thematic search and appraisal approach distinguishes demonstrated findings from contextdependent proposals; no sitespecific savings are attributed to projects without measured evidence. The synthesis suggests that meaningful improvement arises when demand reduction precedes capacity selection, control objectives are coordinated across services, and commissioning data remain usable during operation. Important limitations concern inconsistent performance boundaries, scarce longitudinal Saudi megaproject datasets and insufficient reporting of embodied impacts. An implementation and measurement framework is proposed for scalable evaluation across mixeduse districts.

Keywords: Saudi Arabia; mega projects; energy efficiency; mechanical electrical and plumbing; cooling systems; electrical infrastructure; integrated design; building energy management; lifecycle assessment

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1. Introduction

Saudi Arabia's accelerated development of mixeduse destinations, transport facilities and large building clusters creates an unusually demanding context for energy design. Summer heat places persistent pressure on cooling equipment, while heterogeneous occupancy patterns, phased construction and extensive power distribution require decisions that span conventional engineering disciplines. A highly rated chiller can coexist with poor network efficiency when oversized pumps, restrictive pipework, unsuitable setpoints and uncontrolled simultaneous loads remain unresolved. Consequently, the decisive unit of analysis is the interacting service system rather than an isolated component [10,11,24].

Mega projects amplify the familiar building performance gap. Electrical infrastructure is commonly sized early, cooling and ventilation schemes develop on separate procurement programmes, and operational teams inherit models that are not always consistent with installed assets. As a result, design intent can lose its relationship with meter data, actual operating schedules and maintenance priorities. Research on digital twins and building simulation identifies interoperability and contextual data quality as recurring barriers to turning theoretical performance into sustained savings [1,6,7]. The challenge lies as much in coordination and information quality as in engineering.

The Saudi setting requires particular care in applying international evidence. Desert dust can influence filtration and photovoltaic output; coastal humidity changes latent cooling requirements; large atria and intermittent public events create peaks that are poorly represented by steady occupancy assumptions. Nevertheless, a hot climate alone does not justify specifying maximum capacity for every service. Field investigations of local cooling technologies indicate that weathersensitive strategies can offer improvements, although their effectiveness depends on physical design and operating conditions [11,16,20]. Generalising smallscale trial outcomes to an entire district would be unjustified.

This review approaches integration through a sequence of decisions that operators can verify: establish realistic demand, coordinate plant and networks, connect energy supply with flexible loads, and maintain accountable feedback after handover. The contribution is a critical synthesis linking cooling, electrical and operational evidence to the specific delivery risks of large Saudi developments. It does not claim that a new Saudi project was experimentally tested or that literaturelevel savings can be transferred without calibration.

2. Aim, Objectives and Research Questions

The aim is to critically evaluate how coordinated sustainable MEP design and electrical infrastructure integration can reduce energy demand and wholelife impacts in Saudi mega projects without undermining comfort, resilience or maintainability. The review pursues four objectives: to identify interactions that determine wholesystem efficiency; to compare technical and control strategies across their operating boundaries; to assess practical barriers to integrated

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implementation; and to formulate a measurable decision framework suitable for phased, mixeduse development.

Three research questions guide the synthesis. First, which couplings between cooling, ventilation, water services and electrical networks produce material energy consequences? Second, under what climate, occupancy and data conditions do advanced controls, onsite renewables and storage deliver reliable benefits? Third, which governance, commissioning and measurement practices are necessary to demonstrate enduring improvement at building and district scale?

3. Review Methodology

A structured criticalreview approach was selected because the question spans several interacting technologies and heterogeneous evidence types. Review papers provide conceptual coverage, whereas field studies, numerical evaluations and implementation research test narrower mechanisms. The search domain covered 2020 to 2025 and combined the terms ‘building energy efficiency’, ‘MEP’, ‘HVAC’, ‘district cooling’, ‘electrical distribution’, ‘building automation’, ‘photovoltaic’, ‘storage’, ‘digital twin’, ‘commissioning’ and ‘Saudi Arabia’. Publisherindexed scholarly records and DOIbearing journal pages were used to identify evidence relevant to the questions. The supplied Saudi renewableenergy study informed the structural approach to contextualisation, methods and system interpretation but was not copied as a technical model for building services.

Eligible publications examined operational or lifecycle performance of building systems, provided a clearly identified method or substantial synthesis, and related directly to at least one integration mechanism. Studies were deprioritised where energy outcomes were asserted without defined boundaries, where control results lacked comfort constraints, or where applications could not reasonably inform buildingscale services. For mixed datasets, priority was given to papers explaining baseline selection, climate sensitivity, measurement, control implementation or uncertainty. The final set of 30 DOIlinked sources was organised into six analytical themes: demand and envelope, mechanical services, controls and fault detection, distributed electrical resources, digital information continuity, and carbonoriented procurement.

The appraisal considered evidence type, geographic transferability, system boundary and strength of outcome verification. Field measurement was distinguished from simulation; laboratory proof of concept was not equated with sitewide deployment. Findings were compared narratively rather than pooled statistically because reported denominators differ, including cooling electricity, total building energy, expenditure and peak demand. No fabricated database hit counts, screening totals, formal quality scores or project monitoring datasets are reported. The resulting synthesis is a focused review, not a claim of exhaustive systematic coverage or metaanalysis.

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Causal claims were tested against possible confounding factors: weather, occupancy shifts, changing service levels, tariff assumptions, upstream generation emissions and maintenance interventions. Percentage savings without a specified counterfactual were considered indicative, not transferable. The key question was whether an intervention still improves overall performance after accounting for auxiliary pumps, fans, electrical losses and interacting controls. This emphasis limits misleading conclusions from componentspecific efficiency ratings.

4. Coupled Energy Demand and Design Decisions

Building loads are produced by the interaction of climate, form, envelope, equipment, schedules and occupant behaviour. Reducing sensible solar gains, uncontrolled infiltration and unnecessary ventilation hours can permit smaller cooling plant and electrical feeders, provided critical operating peaks are still captured. Saudi insulation research demonstrates the relevance of envelope characteristics to cooling demand [10]. Yet envelope improvements should be evaluated alongside glazing, daylight, humidity control and thermal storage rather than treated as independent additions to a fixed plant.

In mega projects, the first integration task is reconciliation of diversified loads. Designers should distinguish coincident demand from summated equipment nameplate ratings, and classify resilience requirements according to actual consequences of interruption. A transport concourse, accommodation cluster and entertainment venue may peak at different hours; their diversity offers opportunities for shared plant and storage. Conversely, optimistic diversity factors can create reliability risks. Sensitivity cases must therefore represent event days, extreme weather, partial occupancy and staged commissioning before equipment capacities are locked.

Hydraulic design connects buildinglevel conservation to plant electricity. Oversized distribution loops increase capital cost and can sustain pumping losses over decades. At the other extreme, narrow pipes may reduce material quantities but impose high pressure drops and constrain future changes. Variablespeed pumps, differential pressure resets and appropriate control valve authority deliver advantages only where the network is balanced and the supervisory controller responds to actual critical circuits. Evaluations should include pump power at part load, minimum flow limits and commissioning tolerances rather than relying on designpoint estimates alone.

Ventilation is another crossdisciplinary tradeoff. Demandcontrolled outdoor air can avoid conditioning unneeded air during low occupancy, but overly aggressive reduction risks poor air quality, elevated humidity and pressure instability. Heat recovery may lower cooling or heating loads while increasing fan pressure and maintenance obligations. Designers must calculate net electrical consequences and examine filtration, corrosion and fouling under local site conditions. An integrated model enables the airhandling strategy to be assessed against both indoor environmental quality and distribution energy.

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Domestic hot water, irrigation, wastewater handling and water features are sometimes excluded from the headline cooling discussion despite their material effects on pumps, heat recovery opportunities and controls. For large hospitality and leisure developments, cooptimising hot water production with waste heat from cooling systems can improve resource use. However, heat recovery potential depends on coincident demand and delivery temperature. A promising annual heat balance does not imply practical benefit when useful heat is produced at the wrong time or temperature.

The uncertainty of occupancy deserves attention alongside weather uncertainty. Mixeduse developments can experience extreme event peaks, prolonged low occupancy and irregular facility turnover in the same operating year. Controllers optimised only for the average week may miss the periods that govern capacity and user experience. A robust strategy evaluates representative operating clusters and retains rules for abnormal days, while documenting the operational consequences of conservative safety margins. Such a method creates a clearer basis for equipment modularity and demand flexibility.

5. Sustainable Cooling and Mechanical Plant Integration

Cooling plant efficiency is a function of system temperature, compressor operation, condenser conditions and auxiliary power. Manufacturer performance ratings provide necessary comparisons but do not capture long periods at part load, degraded condenser approach temperatures or chilledwater return temperature problems. Saudi analyses of hybrid evaporative and vapourcompression cooling suggest substantial applicationspecific potential, while local thermal storage investigations show alternative configurations can change electricity requirements [11,20]. These findings support comparative modelling, not universal percentage claims.

Central plants serving multiple structures may exploit diversity and professionalised maintenance, but long distribution runs introduce heat gains and pumping penalties. Decentralised systems reduce some transmission losses yet can duplicate equipment and complicate fleetwide supervision. The better option depends on when loads peak, how the site is arranged, planned expansion, redundancy needs and the abilities of the operating team. A credible feasibility assessment therefore compares full annual plantandnetwork energy under equivalent thermal service, not merely chiller coefficient of performance.

Partload operation deserves priority because many megaproject assets spend years below their intended ultimate occupancy. Equipment staging should respect compressor minimum loads, cooling tower approach temperature, condenser water pumping and distribution bypasses. Thermal storage can move compressor operation away from stressed grid periods, but shifting electricity consumption is not identical to reducing it. Roundtrip thermal losses, charging

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temperatures, tariff structure and grid carbon intensity determine whether storage improves the selected sustainability objective [18,22].

Predictive control literature differentiates physicsbased, datadriven and hybrid models. Modelbased methods express constraints and equipment response explicitly; learned models can adapt to complex behaviour where adequate operational data exist [14,19]. Neither approach removes the need for safe defaults, manual override and protection of occupant comfort. For a newly opened development with little historical data, a simpler transparent controller may outperform an elaborate algorithm trained on unrelated buildings.

Humidity control is particularly important for coastal schemes and highdensity event facilities. An energy optimisation that relaxes supplyair temperature without monitoring moisture can transfer apparent savings into latent discomfort, condensation or fabric deterioration. Field work on humidityaware predictive control demonstrates why moisture dynamics and peak electricity must be treated as explicit performance dimensions [15]. In practice, supervisory optimisation should operate within conservative humidity, ventilation and equipment safety limits.

Commissioning must show that equipment works together correctly, not simply that each machine starts and runs. Frequent examples include simultaneous heating and cooling, pump operation against closed valves, conflicting temperature resets and unavailable sensor feedback. Modern faultdetection studies distinguish model limitations, uncertain fault labels and the importance of system context [26,27,29]. Effective commissioning therefore combines physical tests, trend review and a documented process for correcting deviations after occupancy changes.

A further concern is the distinction between energy conservation and load relocation. Moving a cooling load from late afternoon to the night may reduce network stress but can leave total electricity unchanged or even increase it when storage losses are included. Consequently, the selected objective must be stated before modelling: absolute kilowatthours, coincident kilowatts, electricity cost, carbon impact and resilience are not interchangeable. Reporting all five outcomes allows developers to recognise an intervention's genuine contribution without obscuring tradeoffs.

6. Electrical Infrastructure, Flexibility and Renewable Integration

Electrical efficiency begins with coordinated load estimation, transformer selection, distribution topology, motor controls and power quality. Oversizing may reduce thermal stress but can introduce lowload inefficiencies, while tightly sized systems lose flexibility during expansion. Operational metering should separate cooling plant, pumps, ventilation, lifts, lighting, plug loads and special facilities. Without this allocation, energy managers cannot determine which service drove a peak or whether a demand reduction represents genuine efficiency rather than displaced consumption.

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A shared electrical architecture can support peak management through scheduling, chilledwater storage and controllable ancillary loads. Demand response research emphasises that buildings require interoperable communication, robust forecasts and incentives consistent with user expectations [2]. For Saudi mega projects, the first feasible steps may be deterministic: precooling selected thermal masses, staggering noncritical pumps or adjusting charging schedules while preserving event operations and firelifesafety capacity. Advanced marketbased scheduling should follow, not precede, reliable local control.

Buildingintegrated solar systems can reduce imported electricity, although output varies with orientation, temperature, soiling and available roof or façade area. Reviews of photovoltaic modelling warn against treating rated capacity as equivalent to timematched building supply [5]. When solar availability coincides with afternoon cooling demand, the value may be substantial; when evening events dominate, storage or demand shifting becomes more important. Energy calculations should account for inverter efficiency, degradation, dust maintenance and curtailment.

Battery systems offer fast response, resilience and improved renewable utilisation, but electrical design must consider protection coordination, ventilation, fire safety, cycle degradation and backup priorities. Evidence from building and community storage studies shows that benefits depend strongly on load profiles and management rules [12,13,30]. The strongest business case is not necessarily the maximum installed storage capacity; it is the smallest system that satisfies defined reliability and energy objectives across credible future operating cases.

Microgrids also raise an essential accounting distinction between resilience and energy efficiency. Maintaining critical loads during an outage can justify extra equipment and standby losses, even if annual purchased electricity does not fall. An honest assessment separates grid independence, avoided outages, operating cost, delivered energy and greenhousegas emissions. Comparison should use the same service continuity standard for conventional and integrated alternatives rather than presenting an energy security measure as automatic conservation.

Power quality and controls reliability form another hidden coupling. Frequent switching, variablespeed drives and numerous electronic converters create harmonics and reactive power demands that influence transformer and cable losses. Filters and compensation equipment should be selected through network studies, not generic specifications. Similarly, cybersecurity segregation and communication redundancy must be designed without preventing energy telemetry; otherwise the operational system becomes either unsafe or too opaque to optimise.

7. Digital Coordination, Controls and Lifecycle Information

Building information modelling can reduce coordination errors by connecting spatial constraints, equipment requirements, maintenance access and quantities, but a detailed threedimensional model is not automatically an energy model. Research identifies data completeness,

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interoperability and inconsistent model assumptions as barriers [17,21,23]. A credible integration process identifies the information exchanged between geometric, thermal, hydraulic, electrical and assetmanagement models, assigns responsibility for checking it, and sets rules for updates.

Digital twins should be understood as maintained relationships among assets, measurements and models, rather than dashboards carrying a fashionable label. Review literature identifies monitoring, fault detection, optimisation and maintenance as distinct applications, each requiring a different degree of model fidelity [1,3,4,8]. A transformerhealth model needs electrical condition data; a coolingoptimisation twin needs weather, flow, temperature and service demand. Combining both requires explicit interfaces rather than a claim of universal realtime intelligence.

In practice, a minimum viable digital record may be more valuable than an elaborate yet unmaintained simulation. Each major asset should have a stable identifier, location, rated conditions, commissioning results, sensor map, sequence of operation and maintenance history. Data governance must specify units, timestamps, calibration intervals and treatment of missing points. This enables a plant manager to trace an unexpected electrical peak from feeder metering through a chilledwater pump to its supervisory control command.

Forecasting and predictive maintenance models are vulnerable to changes in occupancy, sensor replacement and equipment retrofit. Studies on automated fault detection show that the training data may not represent actual installation faults, while constructioncontext information can improve diagnostic interpretation [26,27,29]. Therefore, the digital workflow must include model revalidation, operator feedback and escalation rules. False alarms can consume maintenance resources, but missed faults can quietly erode energy performance for months.

Figure 1 presents the proposed hierarchy of integration. The lefttoright progression is deliberate: an optimisation controller cannot compensate indefinitely for inflated demand assumptions or defective distribution design. Similarly, procurement decisions that omit operational measurement eliminate the evidence needed to distinguish design savings from actual performance. Integration should be embedded in contract deliverables, with crossdisciplinary design gates and independent functional testing.

A practical research agenda should also acknowledge operator capability. Sophisticated optimisation can fail when facilities personnel cannot interpret model outputs, adjust constraints or identify stale sensors. Documentation should include control intent, acceptable operating envelopes, alarm response and procedures for restoring a safe fallback mode. Training needs to connect observed trends to physical equipment behaviour. Operator expertise is often treated as secondary, yet it largely determines whether improvements survive beyond the initial demonstration.

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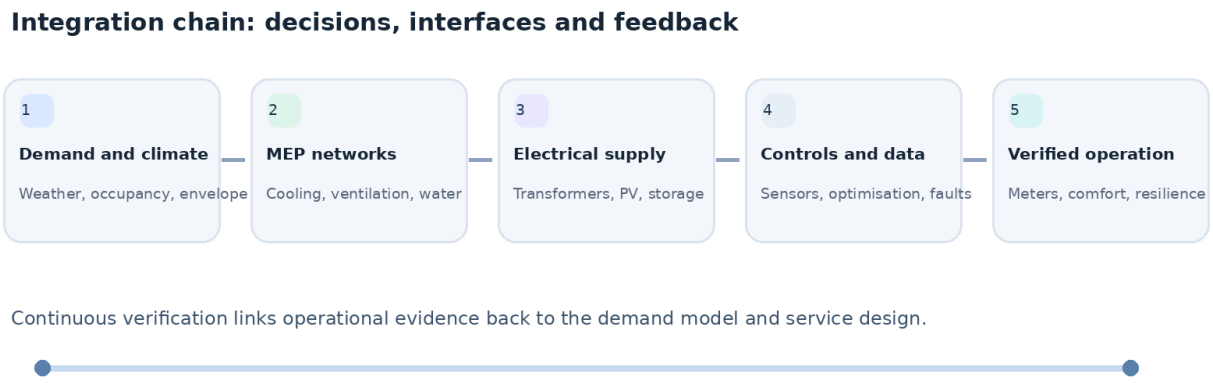


Figure 1. Proposed wholesystem integration sequence (conceptual synthesis; no empirical values).

8. Comparative Evidence and Critical Synthesis

The studies reviewed provide stronger evidence for individual technological mechanisms than for their combined performance across entire mega projects. Local studies support attention to insulation, evaporative strategies and thermally responsive configurations [10,11,16,20]. International evaluations support predictive control, renewable integration and diagnostics under defined conditions [5,14,19,26]. However, research frequently reports different metrics and baseline conditions, preventing defensible aggregation into a single overall savings percentage.

Table 1 compares the principal interventions on a consistent conceptual basis. Its purpose is to expose tradeoffs: a technology that reduces cooling electricity can increase water consumption; renewable generation may lower grid imports without reducing demand; digital controls may save energy only when the physical system can respond. This matrix is more useful to project review boards than rankings built from incompatible casestudy savings figures.

Across the evidence, three recurring failure modes emerge. First, optimisation is performed within a narrow subsystem boundary that omits pumps, fans, power losses or maintenance effects. Second, superior simulated performance is treated as operational proof even though sensors, installation tolerances and users behave differently in practice. Third, energy outcomes are reported without a transparent baseline or weather normalisation. These weaknesses make comparative claims attractive but technically fragile [9,14,24,25].

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Figure 2 translates the literature into a measurement logic with paired input, process and outcome indicators. It deliberately avoids invented project performance values. Once a site has sufficient baseline and postintervention data, individual measures can be assessed using matched operating conditions and uncertainty bands. Portfolio reporting should preserve building typologies because an airport terminal, hotel and outdoor attraction cannot be expected to exhibit identical energy intensities.

Meter placement is a design decision, not an optional operational upgrade. Where several buildings share chilledwater generation, a boundary combining electrical input, chilledwater delivery and distribution losses is required to attribute performance meaningfully. Power meters alone cannot identify whether an apparent efficiency improvement results from reduced cooling demand or poorer indoor service. Calibration records, meter hierarchy and independent validation of key temperatures and flows should form part of the commissioning package and the longterm asset record.

Table 1. Critical comparison of integrated energy measures.

Intervention	Main benefit	Boundary / tradeoff	Evidence anchor
Load and envelope optimisation	Lower thermal and electrical capacity	Weather, service quality, rebound	[10, 24]
Highefficiency cooling and hydraulics	Less plant and pumping electricity	Part load, pressure loss, water use	[11, 14, 20]
Predictive control and diagnostics	Reduced schedule and fault losses	Sensors, humidity, override	[15, 26, 29]
PV, storage and load flexibility	Lower grid import and peaks	Time matching, losses, resilience	[2, 5, 13, 30]
Digital records and coordinated BIM	Better commissioning and accountability	Model validity, data stewardship	[1, 17, 21, 23]

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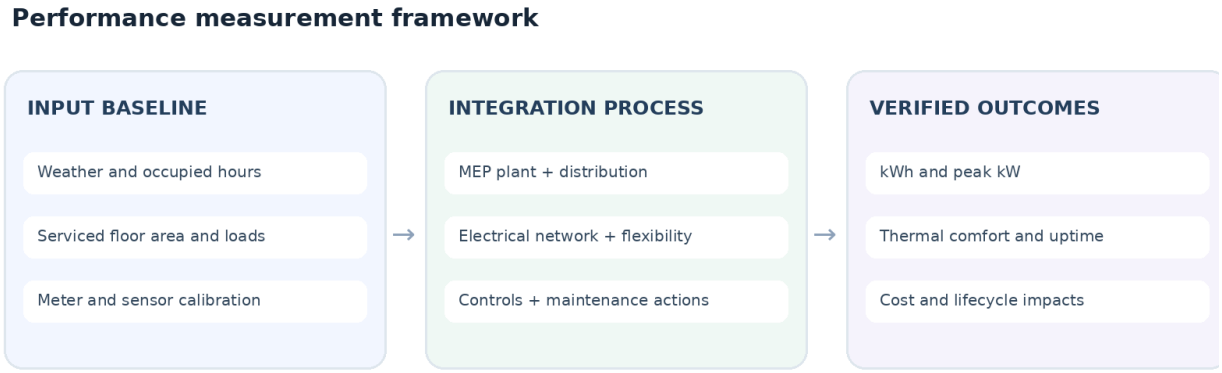


Figure 2. Baselinetooutcome measurement framework for integrated building services (proposed).

9. Implementation Framework for Saudi Mega Projects

A staged governance model is recommended. During concept design, a single energy responsibility matrix should establish service boundary definitions, weather files, occupancy scenarios, electrical diversity and wholelife evaluation criteria. The decisions are sequential but revisable: first reduce demand; then size and configure supply; finally determine the controls and metering necessary to verify results. The evaluation should include future development phases, not solely the openingyear operating condition.

At developed design, integrated workshops should examine critical interfaces rather than only drawing clashes. Examples include condenserwater selection versus electrical peak, variablespeed pump controls versus valve authority, and photovoltaic sizing versus charging or thermal storage. Each interface should have a quantified assumption, named accountable discipline and verification method. Procurement specifications should demand performance at representative part loads and maintainability under dusty, hot and occasionally humid conditions.

During installation, quality assurance should confirm insulation continuity, sensor placement, flow directions, valve leakage, power meter calibration, cable routing and controls connectivity. The greatest longterm penalty may arise from a small unresolved defect repeated across hundreds of similar terminal units. Seasonal commissioning and sitewide trend analysis are needed because factory acceptance and initial startup rarely reproduce maximum summer conditions or eventlevel occupancy.

After opening, a multilayer monitoring system should establish normalised energy intensity, coolingsystem efficiency, peak import, comfort excursions and equipment availability. The recommended denominator is transparent: electricity per conditioned floor area may support one

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comparison, but delivered cooling per electrical input is more informative for central plants. Changes in opening hours, leased area or specialevent schedules should be documented alongside the reported metrics. The proposed indicators are summarised in Table 2.

Responsibility for optimisation should not end when the construction contract closes. A crossfunctional operating forum must include MEP specialists, electrical engineers, facilities teams, information technology, sustainability personnel and users with responsibility for comfort. An escalating intervention pathway is prudent: detect deviation, test sensor validity, identify its likely systemlevel cause, simulate or calculate the corrective action, approve it under safety constraints, and verify the resulting performance. This makes efficiency a maintainable operational capability rather than a oneoff design achievement.

Interdisciplinary decisions become particularly consequential when procurement packages are separated by contract boundaries. Cooling plant vendors may guarantee compressor performance, controls providers may guarantee communication availability, and electrical contractors may guarantee power continuity; none necessarily guarantees combined annual performance. The client should therefore appoint an interface owner with authority to reconcile assumptions, witness integrated functional tests and maintain the handover evidence. This responsibility must be defined before the technical packages become commercially inflexible.

Table 2. Recommended indicators and minimum verification evidence.

Indicator	Measurement and boundary	Acceptance principle
Wholebuilding electricity	Submetered kWh; area, weather and hours	Report baseline and normalisation
Cooling system efficiency	Delivered cooling / total plant and pump kWh	Include distribution auxiliaries
Coincident electrical peak	15–60 min import and critical feeders	Compare equivalent operating cases
Comfort and air quality	Zone temperature, humidity, ventilation	No savings through degraded service
Reliability and faults	Outage exposure, equipment alarms, restoration	Maintain documented critical loads
Lifecycle impact	Material, refrigerant and replacement scenarios	Disclose boundary and uncertainty

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10. WholeLife Carbon and Economic Tradeoffs

Operational electricity is only one component of sustainability. MEP equipment contains metals, refrigerants, electronics, pipework and replacements whose impacts can become material over long asset lifetimes. Recent work on embodied carbon in MEP systems notes important gaps in inventories and consistent reporting [28]. An efficiency measure that requires extensive equipment duplication should therefore be assessed against its manufacturing impacts, expected replacement cycles and actual operating savings.

Wholelife economic appraisal should similarly distinguish capital expenditure, preventive maintenance, energy prices, replacement requirements and residual values. A sophisticated automation solution can be financially poor if its sensors are inaccessible, licence costs are prohibitive or no team maintains the analytic models. Conversely, more durable components and accessible plant layouts may earn benefits through lower downtime and more dependable efficiency even where simple payback calculations appear modest.

A balanced evaluation uses at least three lenses: delivered service quality, lifecycle cost and lifecycle greenhousegas impact. These objectives may conflict. Battery operation optimised for tariff savings may not minimise carbon when marginal grid emissions differ by hour; maximum cooling efficiency may not coincide with peak electrical reduction. An explicit multiobjective assessment prevents the sustainability narrative from masking these conflicts and allows project owners to define acceptable priorities.

11. Research Gaps and Future Directions

The most significant evidence gap is the scarcity of publicly documented, longterm studies that jointly measure mechanical services and electrical infrastructure across Saudi megaproject districts. Published technology evaluations rarely contain the same weather, occupancy, equipment and meter boundaries required for direct comparison. A shared reporting protocol should state climate, service level, system inclusions, measurement intervals, baseline method and uncertainty. Without those disclosures, reported percentage improvements cannot support procurement guarantees.

Second, the literature needs stronger treatment of phased occupancy. A mega project opened at partial capacity may operate for several years in regimes that differ substantially from ultimate design assumptions. Research should investigate modular plant expansion, partload degradation and the energy consequences of temporary commissioning configurations. Third, more studies should examine combined mechanicalelectrical optimisation under realistic network constraints, including harmonics, transformer loading, humidity limits and emergency operation.

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Fourth, better integration of embodied MEP impacts and refrigerant leakage is required. Annual electricity savings are readily measured, while replacement and material burdens are less visible. Standardised lifecycle inventories and prospective maintenance scenarios could expose tradeoffs between centralised and decentralised schemes. Finally, independent postoccupancy studies should test whether performance persists when digital tools, control contractors and building users change over time [4,23,28].

Finally, the durability of the integration architecture matters as much as its launch performance. Expansion phases may introduce new equipment, revised electrical tariffs, alternative occupancy and upgraded renewable resources. Systems should therefore use stable naming conventions, documented data interfaces and modular control logic rather than permanently binding operation to a single equipment supplier. A futureproof design maintains auditable performance calculations and permits incremental improvements without requiring wholesale replacement of functional infrastructure.

12. Review Limitations

This review synthesises selected DOIlinked research rather than an exhaustive census of all studies. It includes publications addressing adjacent building types because directly comparable Saudi megaproject monitoring reports remain limited in the selected evidence. Diverse outcomes and insufficiently compatible baselines preclude a quantitative pooled effect estimate. Recommendations for integrated governance and measurement are consequently reasoned implications from the literature, not empirically validated results from a newly monitored development. The reference list does not substitute for journalspecific technical checks or proprietary similarity assessment. This requires explicit baseline assumptions, independent measurement, periodic recalibration and documented responsibility for correcting operational deviations across the full project lifecycle. This requires explicit baseline assumptions, independent measurement, periodic recalibration and documented responsibility for correcting operational deviations across the full project lifecycle. This requires explicit baseline assumptions, independent measurement, periodic recalibration and documented responsibility for correcting operational deviations across the full project lifecycle. This requires explicit baseline assumptions, independent measurement, periodic recalibration and documented responsibility for correcting operational deviations across the full project lifecycle. The objective is dependable wholesystem performance under real operating conditions. with documented and independently verified project energy performance

13. Conclusion

Sustainable MEP and electrical infrastructure integration is best understood as an operational systemdesign problem. Significant opportunities arise from realistic demand modelling,

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climatesensitive cooling, efficient hydraulic networks, interoperable controls, appropriately configured renewables and storage, and faultaware commissioning. Yet advantages depend on coordinated boundaries, safe control constraints and usable data after handover. For Saudi mega projects, the priority is therefore not simply to acquire higherrated equipment but to create accountable interfaces between service demand, mechanical supply, electrical capacity and verified operating outcomes.

The synthesis supports a practical hierarchy: prevent unnecessary demand, optimise the combined network, deploy flexible resources where justified, and measure sustained performance against transparent baselines. The proposed matrices and figures provide decision and verification tools, not simulated results. Future field studies should test these relationships over complete seasonal cycles in mixeduse Saudi developments and report both energy and wholelife impacts with reproducible assumptions.

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