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Advanced HVAC Optimization for Sustainable High-Rise and Mixed-Use Developments in Saudi Arabia

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Abstract- Saudi Arabia's high-rise and mixed-use developments are entering a period in which cooling performance, occupant experience, carbon reduction and operational resilience must be solved together rather than treated as separate design packages. This review examines advanced heating, ventilation and air-conditioning optimization for towers, podiums, hotels, offices, residences, retail districts and transport-linked developments in hot-arid Saudi conditions. The aim is to synthesize recent evidence from 2020 to 2025 and translate it into a practical optimization framework for projects aligned with Vision 2030, the Saudi Green Initiative and national energy-efficiency programs. A structured review method is used, combining thematic literature screening, technology classification, Saudi contextual analysis and a design-to-operation synthesis. The findings show that the strongest HVAC outcomes are achieved when passive load reduction, high-efficiency central plants, model predictive control, digital twins, fault detection, occupancy analytics and continuous commissioning are integrated from concept design to facility management. The review also highlights unresolved challenges, including limited climate-specific datasets, mixed-use diversity factors, high latent and sensible cooling peaks, maintenance capability gaps, control interoperability and the need for credible measurement and verification. The paper proposes a staged roadmap for sustainable HVAC optimization in Saudi high-rise developments and argues that future competitiveness will depend less on selecting a single premium technology and more on coordinating envelope, plant, controls, data governance and human comfort across the building life cycle.

Keywords: HVAC Optimization, High-Rise Buildings, Mixed-Use Developments, Saudi Arabia, Vision 2030, Model Predictive Control, Digital Twins, Sustainable Cooling

I. INTRODUCTION

High-rise and mixed-use developments in Saudi Arabia are becoming increasingly complex because they combine vertical density, premium indoor comfort expectations, long operating hours and extreme summer cooling demand. Towers in Riyadh, Jeddah, Makkah, Dammam and emerging giga-project districts often include offices, hotels, serviced apartments, retail podiums, restaurants, parking areas and entertainment functions inside a single asset. This functional diversity changes the HVAC problem. Designers must address simultaneous peaks, different occupancy schedules, stack effect, pressure zoning, façade solar gains, air quality, humidity control, fire-life-safety interfaces and plantroom maintainability. In a hot-arid climate, the HVAC system is not a secondary service but the dominant operating system that determines comfort, energy intensity, tenant satisfaction and long-term asset value.

The topic is directly relevant to Saudi Vision 2030 because the Kingdom is investing in dense urban districts, tourism destinations, transport hubs, hospitality assets and new commercial centers while also strengthening sustainability and energy-efficiency governance. National programs led by institutions such as the Saudi Energy Efficiency Center and Tarshid emphasize efficient air-conditioning, thermal insulation, building retrofits and operational savings. This policy direction is consistent with global building-sector decarbonization literature, which identifies cooling, controls and existing-building performance gaps as major barriers to meeting climate targets (IEA, 2023; SEEC, 2025; Tarshid, 2025). For Saudi towers, therefore, HVAC optimization is both an engineering issue and a strategic economic issue.

Recent research has shifted the discussion from equipment efficiency alone to system optimization. Advanced HVAC performance depends on how cooling plants, pumps, air distribution, façade design, occupancy data, weather forecasting and control algorithms interact. Model predictive control can anticipate weather and load changes instead of reacting after comfort has already drifted (Drgoňa et al., 2020; Yang et al., 2022). Digital twins can connect Building Information Modeling, sensors and building management systems to support diagnostics and continuous commissioning (Cespedes-Cubides & Jradi, 2024; Li et al., 2024). Occupant-centric controls can reduce unnecessary conditioning in underused spaces while protecting thermal comfort and indoor environmental quality (Ngarambe et al., 2020; Park et al., 2020). However, these methods are not automatically successful. They require reliable sensors, calibrated models, trained operators, clear ownership of data and a commissioning culture that continues after handover.

The present review responds to a practical gap in the literature. Many studies discuss smart HVAC control in generic commercial buildings, while fewer focus on the combined technical realities of Saudi high-rise and mixed-use assets. The paper therefore reviews recent evidence and proposes a contextual framework for design teams, developers and facility managers. The guiding argument is that sustainable HVAC optimization in Saudi Arabia should start with load avoidance, proceed through efficient system selection, and mature into data-driven operation supported by measurement and verification. This sequence reduces the risk of over-designed plant, fragmented automation and underperforming premium technologies.

II. AIM, OBJECTIVES AND RESEARCH QUESTIONS

The aim of this review is to develop a Saudi-contextual understanding of advanced HVAC optimization for sustainable high-rise and mixed-use developments, with emphasis on energy reduction, comfort, resilience and life-cycle operation. Unlike studies that focus only on one control algorithm or one equipment category, this review treats the HVAC system as an interconnected socio-technical platform. It includes the building envelope, cooling generation, air distribution, controls, data infrastructure, occupant interaction, maintenance processes and policy alignment.

The objectives are fourfold. First, the study identifies the main cooling-performance challenges that distinguish Saudi high-rise and mixed-use developments from low-rise or single-use buildings. Second, it reviews recent optimization strategies, including passive design coordination, high-efficiency chilled-water plants, thermal energy storage, model predictive control, demand-controlled ventilation, fault detection, digital twins and continuous commissioning. Third, it evaluates how these strategies support Vision 2030 goals related to sustainable urbanization, efficient resource use and improved quality of life. Fourth, it proposes a practical implementation roadmap that can be used during concept design, detailed design, handover and operation.

Three research questions guide the analysis. What technical and operational factors most strongly influence HVAC performance in Saudi high-rise and mixed-use assets? Which optimization methods from recent literature offer the highest practical value when adapted to hot-arid Saudi conditions? How can developers and facility managers move from design-stage energy promises to measurable performance during actual operation? These questions are addressed through a structured review of peer-reviewed research, standards, official Saudi energy-efficiency initiatives and lessons from tall-building engineering literature.

III. METHODOLOGY

This paper adopts a structured review methodology inspired by recent perspective and review articles on tall buildings and energy-efficient building systems. The attached Springer reference paper on mega-tall buildings uses a clear sequence of literature review, case analysis, trend assessment and future-prospect synthesis; the present paper adapts that logic to HVAC optimization rather than structural height alone (Konar, 2025). The review was conducted in four stages.

The first stage was literature identification. Recent publications from 2020 to 2025 were prioritized because HVAC control, digital twinning, grid interaction and Saudi energy-efficiency policy are developing rapidly. Search themes included building HVAC optimization, model predictive control, high-rise HVAC operation, digital twins, occupant-centric control, fault detection, thermal comfort, passive cooling in hot-arid climates, building energy simulation and Saudi building energy efficiency. The review included peer-reviewed journals, standards and official Saudi institutional sources where they provided policy or implementation context.

The second stage was screening and thematic classification. Sources were grouped into five themes: cooling-load reduction, high-efficiency system design, smart control and optimization, monitoring and commissioning, and Saudi implementation conditions. This approach avoids the narrowness of algorithm-only reviews and recognizes that real projects fail when design assumptions, control settings and operation practices are not aligned. Literature that focused only on heating-dominated climates, small residential units or unrelated industrial refrigeration was excluded unless it offered transferable principles.

The third stage was synthesis. Evidence was compared across building types and development phases. Special attention was given to high-rise issues such as vertical zoning, stack pressure, condenser-water distribution, multi-tenant schedules, plant redundancy, lift-lobby loads, façade exposure and the interaction between retail podiums and tower uses. For mixed-use projects, the review considered diversity because residential, hotel, office and retail loads rarely peak at the same time. Correct diversity analysis can prevent oversized equipment, while poor assumptions can create both energy waste and comfort risk.

The fourth stage produced a framework and roadmap. The framework links design inputs, plant optimization, control intelligence and performance governance. The roadmap translates the literature into a staged sequence suitable for Saudi developments: passive-first design, right-sized systems, optimized plant rooms, occupant-centric control and continuous commissioning. The review is qualitative, but it is grounded in recent evidence and uses tables and graphical synthesis to support transparent comparison.

IV. SAUDI CONTEXT: COOLING DEMAND, VERTICAL DENSITY AND MIXED-USE COMPLEXITY

Saudi Arabia's climate creates one of the clearest arguments for advanced HVAC optimization. Long periods of high outdoor temperature, intense solar radiation, dust exposure and growing urban heat-island effects produce cooling demand that can dominate annual electricity consumption. In many commercial and residential buildings, air-conditioning represents the largest controllable energy end use. The Saudi Energy Efficiency Center has therefore emphasized air-conditioner performance standards, thermal insulation, building energy codes and efficient HVAC systems as essential parts of national energy-efficiency work (SEEC, 2025). Tarshid's retrofit programs also identify HVAC, lighting, insulation and controls as priority measures for reducing building energy consumption in public and commercial facilities (Tarshid, 2025).

High-rise buildings intensify these issues. Tall façades receive variable solar exposure, upper floors face greater wind pressure, and vertical shafts can move air through stack effect. Cooling distribution must be divided into pressure zones so that pumps, valves, ducts and risers remain controllable and maintainable. In a mixed-use tower, the hotel may require continuous ventilation and humidity control, offices may operate mainly during daytime, apartments may peak in evenings, and retail podiums may generate high internal gains from lighting, kitchens and dense occupancy. A single constant operating strategy cannot suit all zones.

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Saudi urban development adds another layer. Projects are expected to support premium user experience, tourism, smart-city services and sustainability branding. This raises expectations for indoor air quality, acoustic comfort, rapid response to tenant complaints and transparent sustainability reporting. HVAC optimization must therefore balance engineering efficiency with market expectations. Excessive energy-saving measures that create thermal discomfort can damage tenant trust; however, luxury comfort delivered through wasteful operation conflicts with national sustainability goals.

A Saudi-specific HVAC strategy should begin by recognizing that peak cooling capacity and annual efficiency are different problems. Peak capacity protects comfort during extreme design days, while annual efficiency depends on part-load performance, control sequencing, sensor reliability and maintenance quality. Chillers may be efficient in catalog conditions but perform poorly when condenser water temperatures, pump speeds, setpoints and fouled coils are not optimized. Similarly, smart thermostats cannot compensate for an oversized, poorly commissioned air distribution system. The best outcomes are achieved when climate-responsive design, efficient equipment and operational analytics are integrated before construction decisions become fixed.

V. OPTIMIZATION STRATEGIES ACROSS THE HVAC LIFE CYCLE

The first optimization strategy is passive load reduction. In Saudi towers, every watt of avoided solar and envelope load reduces plant size, riser capacity, electrical infrastructure and operating cost. Orientation, glazing ratio, external shading, high-performance glass, roof insulation, airtightness and thermal-bridge control should be assessed before mechanical systems are finalized. Building performance simulation can compare façade options, identify overheating risk and quantify the effect of daylighting and shading on cooling demand (Alqahtani et al., 2023). Passive design does not eliminate mechanical cooling in Saudi Arabia, but it improves the economic and operational feasibility of high-efficiency HVAC.

The second strategy is right-sizing and diversity-based plant design. Mixed-use developments should not simply add the maximum load of every function. Offices, residences, hotels and retail spaces have different daily profiles, and these profiles can be evaluated using dynamic simulation and calibrated benchmarks. Correct diversity reduces unnecessary capital cost and improves part-load efficiency because chillers and pumps operate closer to their efficient ranges. Oversizing remains common because it appears safe during design, but it creates short cycling, poor humidity control, low delta-T syndrome and inefficient pump operation during the much larger number of part-load hours.

The third strategy is optimized chilled-water plant operation. High-rise and mixed-use projects usually depend on central chilled-water plants, whether on site, district-linked or hybrid. Optimization includes chiller sequencing, condenser-water temperature reset, variable primary flow or primary-secondary pumping control, cooling-tower fan optimization, water treatment, differential-pressure reset and thermal energy storage where peak tariff or grid constraints justify it. Studies of super high-rise HVAC operation show that plant complexity can produce higher energy intensity than conventional buildings if control sequences are not tuned to actual load behavior (Jiang et al., 2024).

The fourth strategy is advanced control. Model predictive control uses forecasts and constraints to optimize HVAC operation over a future horizon. It can pre-cool when appropriate, relax setpoints in low-priority zones, limit peak demand and coordinate thermal storage. Its value is especially relevant in Saudi buildings where outdoor temperature and solar gain are predictable, but occupancy and mixed-use schedules vary. State-of-the-art reviews show that MPC is promising because it can handle competing objectives such as comfort, energy, equipment limits and cost, though implementation remains constrained by modeling effort, data quality and operator acceptance (Drgoňa et al., 2020; Yang et al., 2022).

The fifth strategy is occupant-centric control. Instead of conditioning all spaces according to fixed schedules, buildings can use occupancy sensors,

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access-control data, booking systems, CO2 sensors and tenant schedules to adjust ventilation and temperature within acceptable comfort ranges. This is valuable for offices, meeting floors, retail back-of-house areas and amenity spaces with intermittent use. However, occupant-centric control must respect privacy, cybersecurity and service expectations. It should be introduced through clear governance rather than hidden algorithms that frustrate occupants.

The sixth strategy is digital twin-enabled operation. A digital twin connects asset information, sensor data, performance models and operational analytics. It can support fault detection, chiller performance tracking, valve diagnostics, comfort complaint analysis and energy measurement and verification. Recent reviews emphasize that digital twins are most useful when they are linked to practical decisions, not when they remain isolated visualization tools (Cespedes-Cubides & Jradi, 2024; Li et al., 2024). For Saudi high-rise assets, digital twins can also preserve knowledge after construction teams leave and facility management teams take over.

The seventh strategy is continuous commissioning. Many buildings are efficient only on paper because setpoints drift, sensors fail, dampers stick, coils foul and overrides remain active after temporary complaints. Continuous commissioning uses trend data, benchmarks, alarms and periodic testing to keep the building aligned with design intent. This process is essential for high-rise and mixed-use assets because small errors can multiply across hundreds of zones. It also supports environmental, social and governance reporting because savings are measured rather than assumed.

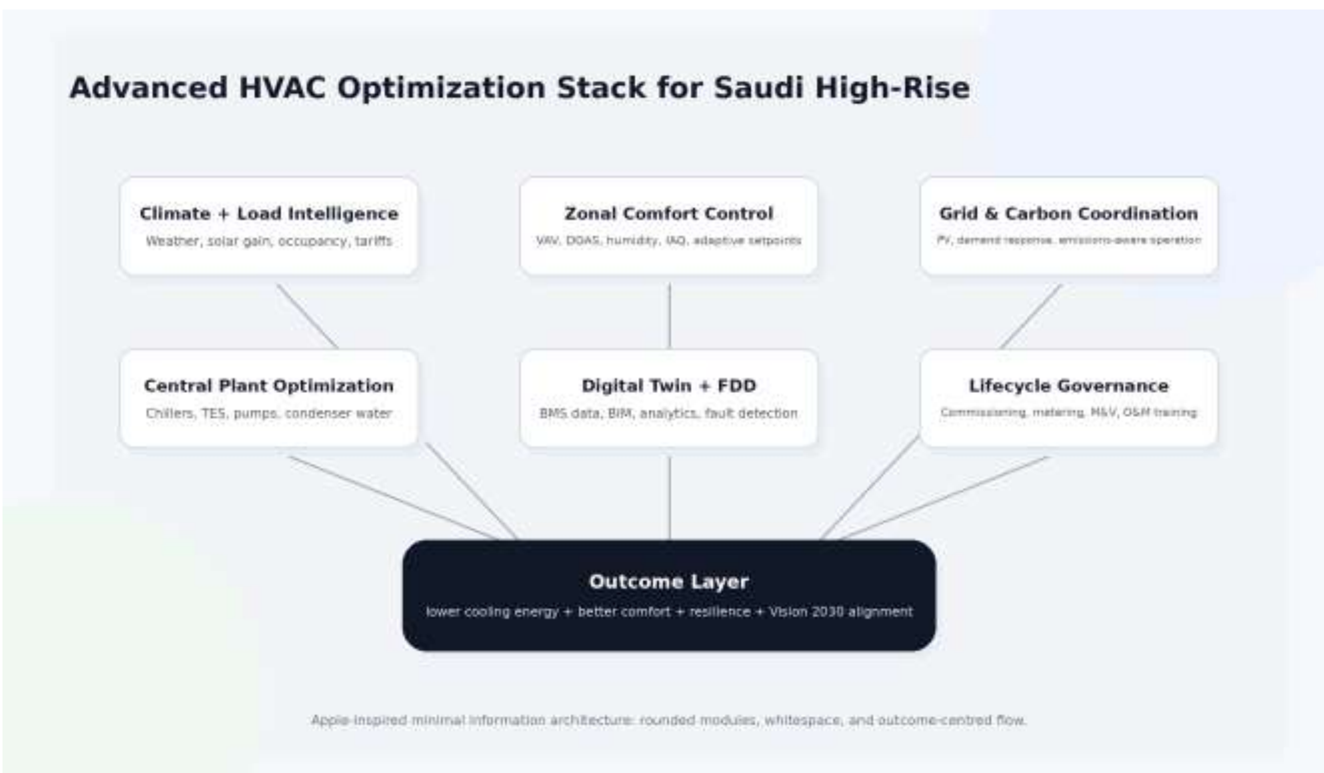

Figure 1. Integrated HVAC optimization framework for Saudi high-rise and mixed-use developments.

Optimization area	Saudi high-rise relevance	Typical measures	Expected benefit
Envelope and passive loads	Solar radiation and long cooling seasons increase façade impact	Shading, high-performance glazing, airtightness, roof insulation, thermal-bridge control	Lower peak load, smaller plant, reduced annual cooling energy
Plant design	Large mixed-use assets require reliable chilled-water generation	Efficient chillers, VFD pumps, condenser-water reset, thermal energy storage	Improved part-load efficiency and peak-demand management
Air-side systems	Different zones need different comfort and ventilation profiles	VAV optimization, DOAS, CO2 control, supply-air reset, pressure reset	Better comfort with less fan and cooling energy
Controls and analytics	BMS data are often underused after handover	MPC, FDD, digital twins, trend analytics, alarms rationalization	Persistent performance, fault reduction and measurable savings
Operations governance	Savings decay when operators lack tools or training	Continuous commissioning, M&V, operator dashboards, maintenance KPIs	Long-term alignment between design intent and real operation

Table 1. HVAC optimization areas and expected performance value in Saudi high-rise projects.

VI. KEY CHALLENGES AND TRADE-OFFS

Advanced HVAC optimization faces several constraints. The first is data reliability. Sensors in large buildings may be poorly calibrated, mislabeled or disconnected from analytics platforms. A digital twin built on incorrect point mapping will produce misleading recommendations. Therefore, data governance, naming conventions, commissioning records and cybersecurity protocols are as important as algorithms.

The second challenge is interoperability. Saudi mixed-use assets often include equipment from multiple suppliers, separate tenant fit-outs and different building management system packages. Without open communication protocols and clear integration specifications, the plant, air-side systems, meters and tenant systems cannot be optimized together. Interoperability should be written into procurement documents before vendor selection.

The third challenge is human capability. Optimization tools may be purchased during construction but ignored during operation if facility teams are not trained. Operators need dashboards that explain recommended actions, not black-box outputs. Contracts should also reward measured performance rather than only reactive maintenance. Otherwise, the safest behavior for operators is to keep systems running continuously at conservative setpoints, which protects comfort but wastes energy.

The fourth challenge is balancing energy reduction with indoor environmental quality. Excessive ventilation reduction can harm air quality, and aggressive temperature setbacks can damage tenant satisfaction. Standards such as ASHRAE 55 and ASHRAE 62.1 provide comfort and ventilation boundaries, while high-performance sequences such as ASHRAE Guideline 36 support more consistent control logic. The Saudi context requires careful adaptation because comfort expectations, dress norms, prayer times, Ramadan schedules and hospitality requirements may differ from assumptions in international studies.

The fifth challenge is climate resilience. Future cooling systems must respond to hotter summers, dust events, possible water constraints and grid stress. Resilience may require redundancy, maintainable filtration, condenser-water monitoring, backup power coordination, emergency ventilation modes and demand-response capability. Some efficiency measures reduce redundancy if applied without risk analysis; for example, minimizing spare capacity can reduce capital cost but weaken resilience during extreme heat or equipment failure.

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The sixth challenge is cost justification. Premium controls, sensors, analytics and high-performance equipment require capital expenditure. Developers may hesitate if benefits are uncertain or if the asset will be sold before operational savings are realized. This can be addressed through life-cycle costing, green finance, energy performance contracts and measurement and verification. Tarshid's retrofit model demonstrates how institutional energy-efficiency programs can help overcome owner-capital barriers by structuring projects around savings and performance outcomes (Tarshid, 2025).

VII. PROPOSED FRAMEWORK FOR SAUDI HIGH-RISE HVAC OPTIMIZATION

The proposed framework has four connected layers. The first layer is climate and load intelligence. It includes weather files, solar analysis, thermal zoning, occupancy profiles, plug-load estimates, kitchen and retail loads, hotel laundry loads, prayer and event schedules, and façade performance. This layer should be created early because it influences plant capacity, shaft space, riser sizing and electrical infrastructure.

The second layer is system architecture. It covers chilled-water generation, district cooling interfaces, condenser-water systems, thermal energy storage, dedicated outdoor-air systems, energy recovery, variable air volume systems, fan-coil or chilled-beam options, heat rejection, pressure zoning and maintainability. The preferred architecture should be selected through life-cycle assessment rather than lowest initial cost. For example, a high-efficiency chiller is less valuable if the pumping arrangement creates permanent excess pressure or if the condenser-water system cannot maintain stable temperatures.

The third layer is control intelligence. It includes demand-controlled ventilation, supply-air temperature reset, static-pressure reset, chilled-water temperature reset, chiller sequencing, predictive pre-cooling, humidity limits, occupancy-based scheduling and alarm rationalization. Advanced methods such as MPC and reinforcement learning should be introduced gradually after robust baseline sequences are functioning. A building with unstable basic control will not benefit from complex algorithms.

The fourth layer is performance governance. This includes metering, dashboards, fault detection, operator training, tenant engagement, maintenance planning and measurement and verification. Governance turns optimization from a design claim into an operating discipline. For Saudi high-rise projects, the governance layer should remain active throughout the defects-liability period and continue into normal facility management. It should also produce evidence for sustainability certifications, ESG reporting and owner decision-making.

Figure 1 summarizes the framework as an integrated stack. Figure 2 presents the implementation roadmap. Together, they show that HVAC optimization is not a one-time calculation but a sequence of decisions extending from planning to operation. The framework is intentionally modular so that it can support new projects, retrofits and phased mixed-use developments.

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Figure 2. Staged roadmap for design-to-operation HVAC optimization.

Challenge	Risk in Saudi mixed-use towers	Mitigation strategy
Oversizing	High capital cost, short cycling, weak humidity control and inefficient part-load operation	Use dynamic simulation, diversity profiles and staged capacity planning
Poor sensor quality	Wrong analytics outputs and unreliable control decisions	Commission sensors, verify point naming and apply calibration routines
Fragmented BMS integration	Plant, tenant and podium systems cannot be optimized together	Specify open protocols, integration testing and shared data architecture
Comfort complaints	Operators override efficiency measures permanently	Define comfort bands, escalation rules and occupant communication procedures
Maintenance capability gaps	Advanced technologies become inactive or poorly tuned	Train operators, simplify dashboards and use performance-based O&M contracts
Climate resilience	Extreme heat, dust and grid stress increase operational vulnerability	Plan redundancy, filtration, emergency modes, demand response and seasonal commissioning

Table 2. Key implementation risks and mitigation strategies for Saudi mixed-use towers

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VIII. DISCUSSION

The review indicates that Saudi high-rise HVAC optimization should be treated as a national competitiveness issue. Cooling demand influences electricity infrastructure, operating expenditure, carbon emissions and user experience. As Riyadh and other cities compete for regional headquarters, tourism and investment, high-performance indoor environments will become part of real estate value. Buildings that can demonstrate lower energy use, stable comfort and transparent data will be more attractive to owners, tenants and regulators.

The most important insight is that technology hierarchy matters. Passive load reduction and right-sizing should precede advanced controls. Efficient plant selection should precede digital twin deployment. Measurement and verification should accompany every claim. When this hierarchy is reversed, projects risk buying sophisticated platforms that merely reveal avoidable design or commissioning mistakes. Conversely, when the hierarchy is respected, each later layer amplifies the previous one.

The findings also show that Saudi Arabia has strong implementation potential because the policy environment already recognizes energy efficiency. SEEC standards, Tarshid retrofits, Saudi Green Initiative commitments and Vision 2030 urban transformation provide institutional support. The remaining gap is project-level execution. Design consultants, contractors, controls vendors and facility teams must share data and accountability. Procurement should require trend-point lists, naming standards, open protocols, seasonal commissioning and post-occupancy tuning.

For research, the main gap is local evidence. More published case studies are needed on Saudi high-rise HVAC operation, including measured energy intensity, comfort performance, fault types, chiller plant efficiency, and digital twin outcomes. Studies should report not only simulated savings but also persistence of savings after one, two and three years of operation. Researchers should also examine mixed-use load diversity in Saudi cities because imported schedules may not reflect local retail, hospitality and residential behavior.

For practice, the immediate opportunity is to use existing BMS data more effectively. Many buildings already collect thousands of points but do not convert them into operational knowledge. Simple analytics such as simultaneous heating and cooling detection, abnormal valve positions, low chilled-water delta-T, excessive after-hours operation and sensor drift can produce quick savings. These measures can prepare organizations for more advanced MPC and digital twin applications.

A further implication is that Saudi design teams should strengthen early collaboration between architects, facade consultants, MEP engineers and controls specialists. In many towers the envelope is fixed before the cooling strategy is fully tested, which can lock the project into larger chillers, larger risers and higher electrical demand. A coordinated concept stage can compare facade heat gain, daylight, view quality and cooling plant impact at the same time, allowing developers to choose options that improve both architectural quality and operational performance.

Mixed-use scheduling also deserves more attention. A hotel ballroom, a retail food court, premium office floors and serviced apartments have different internal heat gains and ventilation requirements. When all spaces are treated as if they peak simultaneously, equipment becomes oversized and inefficient. When diversity is studied too aggressively, comfort risk increases during events or seasonal tourism peaks. The balanced approach is to model realistic scenarios, retain safe redundancy and use controls that can prioritize critical zones during extreme weather.

Water and maintenance considerations are equally important in hot-arid operation. Cooling towers, filters, coils and heat exchangers can lose efficiency rapidly when water quality, dust loading or cleaning frequency are neglected. Optimization should therefore include maintenance access, chemical treatment, filtration strategy and spare parts planning. These practical issues are sometimes less visible than digital dashboards, but they determine whether a high-performance plant remains efficient after several summers.

Procurement can either support or weaken optimization. Performance requirements should specify metering points, trend intervals, open protocols, fault-detection rules, seasonal commissioning tasks and handover training. Tender documents should also require the controls contractor to demonstrate sequences under low load, peak load and emergency modes. This reduces the common problem of excellent design reports being followed by incomplete site implementation.

For existing buildings, the most realistic path is staged improvement rather than immediate replacement. Owners can begin with energy audits, sensor correction, schedule cleanup, chilled-water temperature reset, pump optimization and fault detection. These measures can identify low-cost savings and create the data discipline needed for future digital twin or MPC deployment. Retrofit planning should prioritize measures with measurable savings and minimal disruption to tenants.

The review finally suggests that Saudi Arabia can develop a specialized knowledge base for cooling-led smart buildings. Local universities, consultants, developers and facility managers should publish anonymized performance data and case studies. Such evidence would help move the sector away from imported assumptions and toward Saudi-calibrated benchmarks for high-rise offices, hospitality towers, malls and residential mixed-use assets.

IX. CONCLUSION

This review examined advanced HVAC optimization for sustainable high-rise and mixed-use developments in Saudi Arabia. The analysis shows that HVAC performance is shaped by climate, vertical density, mixed-use diversity, control quality, maintenance capability and institutional energy-efficiency goals. In Saudi conditions, cooling optimization is central to sustainable urban development because HVAC systems dominate comfort delivery and represent a major opportunity for energy and carbon reduction.

The paper concludes that the most effective approach is integrated and life-cycle based. Passive design reduces cooling loads before equipment is selected. Dynamic simulation and diversity analysis prevent oversizing. Efficient chilled-water plants and variable-flow systems reduce operating cost. Model predictive control, occupant-centric strategies and digital twins improve real-time performance when supported by reliable data. Continuous commissioning then protects savings against operational drift.

The review also identifies key limitations. Advanced controls can fail when data are poor, procurement is fragmented, operators are not trained or comfort expectations are ignored. Saudi projects should therefore avoid technology-led optimization and instead adopt performance-led governance. Every major high-rise and mixed-use development should define energy targets, comfort targets, metering plans, data ownership, commissioning responsibilities and measurement and verification procedures before handover.

Future Saudi developments can become regional benchmarks if they combine architectural ambition with disciplined MEP performance. Advanced HVAC optimization supports Vision 2030 not only by saving energy but also by improving quality of life, strengthening asset value, supporting green jobs and demonstrating that dense urban growth can be comfortable, resilient and sustainable in a hot-arid climate.

This synthesis therefore prioritizes a disciplined operating model for Saudi high-rise HVAC optimization. Developers should define comfort, energy, carbon and resilience targets at concept stage, then protect those targets through procurement, commissioning and facility management. Consultants should translate climate-calibrated simulations into practical plant capacities, zoning strategies and control sequences that operators can understand. Contractors should verify sensors, meters, valves, pumps and dampers before handover, because unreliable field data can weaken every digital tool. Facility managers should use dashboards to review chilled-water delta-T, after-hours operation, filter condition, humidity trends, tenant complaints and abnormal alarms on a regular schedule. Owners should also connect performance contracts, green finance and sustainability reporting to measured outcomes rather than design promises alone. For mixed-use towers, this governance must remain flexible enough to manage hotel events, office occupancy, residential evening loads, retail peaks, dust episodes and extreme heat. When these practices are combined, advanced technologies such as MPC, FDD and digital twins become practical enablers rather than decorative software. The long-term opportunity is to create Saudi-calibrated benchmarks, train specialized cooling operators, reduce waste, improve occupant confidence and demonstrate that vertical urban growth can support regional competitiveness, dependable comfort and documented environmental excellence. This approach also supports tenant retention, asset valuation, regulatory readiness and the wider Vision 2030 objective of delivering efficient, attractive and resilient places for residents, visitors and investors across the Kingdom.

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