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Review article

Design-operation-performance coupling in contemporary HVAC systems: A system-level review

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ABSTRACT

Heating, ventilation, and air-conditioning (HVAC) systems play a decisive role in the energy consumption, indoor environmental quality, and carbon footprint of contemporary buildings. Despite significant advances in high-efficiency equipment and control technologies, a persistent gap remains between nominal efficiency ratings and realised in-use performance. This discrepancy is primarily driven by dynamic operating conditions, part-load behaviour, climatic variability, and cross-layer misalignment between system design, operational control, and environmental demands. This review adopts a system-level perspective to examine how HVAC performance is shaped through the coupling of design configuration, equipment modulation capability, supervisory control architecture, and sensible-latent load interaction. Rather than treating system typologies, control strategies, and performance metrics as isolated domains, the study organises existing literature within a structured design-operation-performance coupling framework. Centralised, decentralised, and hybrid HVAC configurations are critically reviewed with particular emphasis on part-load thermodynamics, ventilation-humidity interaction, and control coordination under real building conditions. The analysis reveals that nominal efficiency indicators such as the coefficient of performance (COP) and seasonal ratings represent equipment potential rather than guaranteed operational outcomes. Performance degradation commonly emerges from conservative sizing practices, limited turndown capability, inadequate supervisory coordination, and humidity-dominated operating regimes, especially in ventilated and humid climates. The review further highlights that effective performance realisation depends less on individual component efficiency and more on the coherence between system architecture, modulation strategy, and control hierarchy. By synthesising experimental findings, field studies, and simulation-based research, this work provides an integrated evaluation logic for interpreting HVAC efficiency beyond static ratings. The proposed framework supports more reliable performance assessment, informs design and commissioning practices, and contributes to narrowing the persistent gap between predicted and realised HVAC performance in contemporary low-carbon buildings.

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1. INTRODUCTION

Modern buildings must provide adequate thermal comfort, good indoor air quality, and healthy humidity levels. These conditions protect human health, improve productivity, preserve building durability, and support efficient energy use (Dimitroulopoulou et al. 2023; Cuce et al. 2024; Maiques et al. 2025). HVAC systems are now considered key components of modern building design rather than simple auxiliary installations. Their design and operation have major effects on energy use, operating costs, and the environmental performance of buildings (Cuce and Cuce 2017). The urgent challenge of climate change has made it necessary to reconsider how buildings provide heating, cooling, ventilation, and dehumidification. The building sector is responsible for almost 40% of final energy consumption and a comparable share of greenhouse-gas emissions in many industrialised and developing economies (Cuce et al. 2025a; Cuce et al. 2025b; Cuce and Cuce, 2025). Therefore, HVAC system performance has become a key factor in the life-cycle energy profile of buildings. Optimising these systems can improve energy efficiency, lower operational costs, and support wider decarbonisation goals (Cuce 2025a; Simpeh et al. 2022; Bera et al. 2025).

Over the past two decades, the design philosophy of building HVAC systems has changed significantly. The focus has moved beyond meeting peak heating and cooling loads under fixed design conditions. HVAC systems are now considered integrated parts of the architectural, structural, and operational framework of buildings (Ellis and Mathews 2002; Reddy et al. 2024; Alvur et al. 2025; Hatanaka et al. 2017). This shift has been supported by advances in computational modelling, high-efficiency equipment, sensor-based automation, and stricter energy regulations, including the European Union's Energy Performance of Buildings Directive and similar international codes (Kim et al. 2022; Olatunde et al. 2024; Papadopoulos 2016). Modern HVAC systems are expected to operate dynamically. They must respond to changing internal loads, variable outdoor conditions, and complex occupancy patterns while reducing primary energy use and supporting low- or zero-carbon energy integration (Tejani and Khandelwal 2023). As a result, the traditional distinction between centralised and decentralised HVAC systems has become less clear. Hybrid solutions are now widely used, including VRF systems combined with dedicated outdoor air systems, radiant panels supported by displacement ventilation, and desiccant-based dehumidification regenerated by waste or renewable heat (Marrasso et al. 2019; Yau et al. 2024; Saber et al. 2014).

The operation of HVAC systems has also changed substantially. Buildings must now provide thermal comfort and indoor environmental quality while also reducing energy use intensity and peak electrical demand (Wang et al. 2019; Manz et al. 2014). Advanced control strategies, from conventional PID control to model predictive control and artificial intelligence-based self-learning algorithms, allow real-time adjustment of set-points, airflow rates, and operating schedules in accordance with the sensor data, weather forecasts, and occupancy profiles (Cheng and Lee 2019). In addition, building energy management systems and cloud-based platforms enable predictive maintenance, fault detection, and continuous commissioning (Aghili et al. 2025; Taheri et al. 2024). Hence, HVAC performance depends not only on the efficiency of individual components, such as chillers, boilers, heat pumps, air-handling units, and desiccant wheels, but also on control quality and integration with other building systems, including the envelope, lighting, and renewable energy technologies (Satyavada and Baldi 2016; Li et al. 2015).

At the same time, the expectations of building owners, operators, and occupants have become more demanding (Chappells and Shove 2005; Sharma and Mistry 2023). Modern commercial and institutional buildings often have variable occupancy densities, diverse internal heat gains, and stricter indoor air quality requirements (Chua et al. 2013; Goetzler et al. 2016). Poor indoor air quality is associated with negative health effects and reduced cognitive performance. This has increased the need for HVAC systems that provide not only thermal comfort but also clean and healthy indoor air. Particular attention is now given to particulate matter, volatile organic compounds, pathogens, and humidity control, especially after the COVID-19 pandemic. In parallel, nearly zero-energy building targets and certification schemes such as BREEAM, LEED, and WELL require HVAC systems to contribute to lower energy use, reduced greenhouse-gas emissions, and improved occupant well-being (Abouleish 2020; Cuce 2026; Faulkner et al. 2022).

Climate change has further increased the importance of HVAC resilience and adaptability. More frequent heatwaves, cold spells, and extreme humidity events challenge traditional sizing methods based mainly on historical weather data and fixed assumptions about occupancy and internal gains (de Rubeis et al. 2020; Wang et al. 2025; Jurjevic and Zakula, 2023; Li et al. 2012). These methods may no longer reflect future operating conditions, especially as remote working and flexible occupancy patterns change building load profiles. Advanced load estimation methods, digital twins, and simulation tools such as EnergyPlus, DesignBuilder, and TRNSYS can help engineers evaluate HVAC performance under different future scenarios (Elnour et al. 2024). These tools are also useful for assessing part-load operation, where HVAC systems spend much of their operating time and where full-load efficiency indicators such as COP may provide limited information.

Environmental concerns have also encouraged the development of alternative HVAC configurations and working fluids (Ness and Xing 2017; Cuce 2025c). The phase-down of high-global-warming-potential refrigerants under the Kigali Amendment and the wider use of heat pumps have reshaped mechanical services engineering (Protocol and Layer 2022). Passive and hybrid strategies, such as night-time ventilative cooling, earth-to-air heat exchangers, and indirect evaporative cooling, can further reduce mechanical energy demand when properly integrated with active systems (Jiménez-Anzar et al. 2025; Kouki et al. 2025; Patin and Rousse 2025; Hasan et al. 2025). In hot and humid climates, sorption-based and membrane-assisted dehumidification technologies are also gaining attention because they can improve humidity control while reducing energy consumption. These developments show that HVAC design cannot be separated from building physics, energy policy, and environmental sustainability (Cuce et al. 2025a; Cuce et al. 2025b; Cuce and Cuce 2025).

Despite these technological advances, many buildings still consume more energy than predicted. This difference between expected and actual performance is commonly known as the performance gap (Mahdavi et al. 2021). Post-occupancy evaluations show that poor commissioning, inadequate control logic, inappropriate operation, and occupant behaviour can lead to excessive energy use and reduced indoor environmental quality (Jain et al. 2020). Therefore, HVAC design should not end with equipment selection and installation. It should also include continuous monitoring, data-driven diagnostics, regular commissioning, and occupant engagement (Di Stefano et al. 2023; Salzano et al. 2025). The increasing complexity of HVAC systems also requires facility managers to interpret performance data and maintain compliance with evolving standards and regulations (Khazaii 2016; Sanjeevi et al. 2025).

For these reasons, there is a need for comprehensive studies that bring together current knowledge on HVAC design, operation, and real-world performance. Such studies should connect theoretical modelling with practical operation and consider the combined effects of system selection, control strategy, climate, occupancy, and building envelope characteristics (Palladino 2023). By synthesising experimental and simulation-based research across different building types, including commercial towers, healthcare facilities, educational buildings, and residential complexes, researchers can identify best practices and future improvement pathways (Abuimara et al. 2022; Kim et al. 2022; Shi and Chen 2021).

This review addresses an important question in contemporary HVAC research: why does nominal equipment efficiency often differ from actual building performance under dynamic operating conditions? Instead of examining design configuration, part-load behaviour, ventilation strategy, and control architecture separately, this review considers them through an integrated design-operation-performance framework. This framework links four main levels: architectural and sizing decisions, equipment modulation and stability, supervisory control and operational coordination, and climatic sensible-latent load variability. By organising performance degradation mechanisms across these interacting levels, the review shows that performance gaps are not caused only by inefficient components. They often result from poor alignment between design assumptions, control strategies, system operation, and real building conditions. In this way, the review shifts the focus from equipment-based efficiency ratings to system-level performance realisation in contemporary low-carbon buildings.

2. SCOPE AND STRUCTURE OF THE REVIEW

This review adopts a structured system-level perspective centred on the interaction between design configuration, operational dynamics, and performance outcomes in contemporary HVAC systems. Rather than providing an exhaustive catalogue of technologies, this study focuses on how architectural choices, part-load behaviour, control coordination, and climatic conditions collectively shape realised efficiency in modern building applications. The scope includes centralised, decentralised, and representative hybrid HVAC configurations, examined with particular emphasis on part-load operation, sensible-latent load interaction, ventilation coupling, and supervisory control architecture. These dimensions are analysed in relation to the divergence between nominal efficiency metrics and field-measured performance, commonly described as the building performance gap. Detailed component-level thermodynamic derivations, refrigerant cycle optimisation studies, and technology-specific experimental apparatus descriptions fall outside the boundary of this review. The analysis remains focused on system-level interactions and dynamic operational behaviour consistent with the design-operation-performance coupling framework introduced in Section 1. The thematic boundaries guiding the discussion are summarised in Table 1.

Table 1. Scope of the review and thematic coverage.

Framework Layer	Analytical Focus	Key Issues Addressed	Relation to Performance Realisation
Design Layer	System architecture & sizing	Centralised vs decentralised; oversizing; ventilation configuration	Determines nominal efficiency potential
Equipment Layer	Modulation capability	Variable-speed drives; turndown limits	Influences part-load stability
Operational Layer	Control logic & coordination	PID, MPC, supervisory integration	Governs real-time performance realisation
Climatic Layer	Sensible-latent load dynamics	Humidity dominance; ventilation coupling	Alters the effective operating envelope
Performance Layer	Evaluation metrics	COP, IPLV, seasonal indices; performance gap	Reflects divergence between rated and realised efficiency

The remainder of the paper is structured as follows. Section 3 classifies contemporary HVAC system typologies. Section 4 examines operational and control-oriented performance drivers. Section 5 discusses performance evaluation and the implications of part-load and humidity-driven behaviour for realised efficiency. Section 6 outlines broader design and policy considerations, followed by concluding remarks. Finally, the rest are the conclusions and future research directions, respectively.

2.1. LITERATURE REVIEW METHODOLOGY

The methodological approach of this review is designed to examine HVAC system performance from a system-level perspective, with particular emphasis on the interaction between design configuration, operational behaviour, and realised efficiency in real building environments. Instead of treating HVAC technologies as isolated components or control algorithms, the review framework prioritises studies that explicitly address dynamic operation, part-load behaviour, and performance divergence between design-stage expectations and in-use conditions. To achieve broad yet focused coverage, the literature search is carried out across three major academic databases: Web of Science, Scopus, and Google Scholar. These platforms are selected to capture both high-impact journal publications and interdisciplinary research spanning HVAC engineering, building physics, control systems, and building energy performance assessment. The search strategy relies on iterative keyword combinations aligned with the conceptual focus of the study. Search terms include expressions related to performance realisation and system interaction, such as “HVAC performance gap”, “part-load operation”, “system oversizing”, “sensible and latent load interaction”, “ventilation-cooling coupling”, “VRF and hybrid HVAC systems”, “dedicated outdoor air systems”, “HVAC supervisory control”, and “real-world HVAC efficiency”. Keyword groupings are progressively refined to prioritise studies addressing operational dynamics and cross-layer effects rather than nominal equipment ratings alone. The reviewed literature predominantly covers the period from approximately 2010 to 2026, reflecting the rapid expansion of research on variable-speed technologies, advanced control architectures, humidity-aware cooling strategies, and post-occupancy performance evaluation. Earlier publications are included selectively where they provide essential theoretical grounding for efficiency metrics, part-load thermodynamics, or control principles that underpin more recent developments. Articles are retained based on the following selection principles:

1. publication in peer-reviewed international journals and availability in English;
2. relevance to HVAC system operation in buildings, supported by field measurements or high-resolution simulation;
3. explicit consideration of part-load behaviour, control coordination, ventilation strategy, or climatic effects; and
4. discussion of operational performance indicators, including seasonal efficiency trends, energy use intensity, or deviations between predicted and measured outcomes.

Non-refereed material and conference papers are generally excluded unless they offer unique system-level insights not replicated in journal literature. Following screening, the selected studies are organised into thematic groups corresponding to system architecture, operational control strategy, climatic load characteristics, and performance evaluation perspective. This classification enables cross-comparison of recurring performance degradation pathways and facilitates the synthesis of evidence supporting the proposed design-operation-performance coupling framework. Through this methodological structure, the review integrates diverse strands of HVAC research into a coherent analytical narrative, enabling a deeper understanding of why high nominal efficiency does not necessarily translate into equivalent operational performance in contemporary buildings.

3. CLASSIFICATION OF HVAC SYSTEMS IN CONTEMPORARY BUILDINGS

HVAC systems employed in contemporary buildings may be broadly classified in accordance with their mode of air distribution, level of centralisation, and degree of integration with other building subsystems (Alghamdi and Krarti 2025; Michailidis et al. 2025). Even though numerous hybrid and bespoke configurations exist in practice, the majority of HVAC applications reported in the literature can be grouped into a limited number of representative system typologies (Marrasso et al. 2019). Establishing a clear classification framework is essential for meaningful comparison of design approaches, operational strategies, and performance outcomes across different building contexts. In general terms, HVAC systems may be categorised as centralised, decentralised, or hybrid systems (Figure 1) (Cuce and Cuce 2026). This classification reflects differences in physical system layout, control strategy, scalability, maintenance requirements, and part-load performance. The following subsections outline the defining characteristics of each category, with emphasis on their relevance to modern building applications.

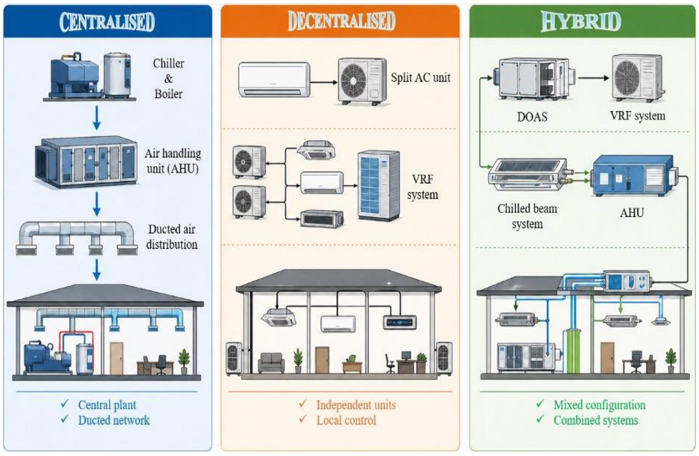

Figure 1. Classification of HVAC systems in contemporary buildings.

3.1. CENTRALISED HVAC SYSTEMS

Centralised HVAC systems generate heating, cooling, and ventilation at a central plant. Conditioned air or water is then distributed to different zones of the building (Korolija et al. 2011). Common examples include constant air volume (CAV) (Aktacir et al. 2006) and variable air volume (VAV) systems supplied by air-handling units (AHUs) (Nandagopal 2024). Hydronic systems using chillers (Ding et al. 2025), boilers (Cuce 2025b), and fan-coil terminals (O'Neal and Yin 2020) are also widely used.

The main advantage of centralised systems is their ability to serve large floor areas efficiently. They can also provide effective filtration, humidity control, and system monitoring (Ahmed et al. 2026). Therefore, they are commonly used in commercial offices, healthcare facilities, and institutional buildings where indoor air quality requirements are strict (Ramadan et al. 2025). However, their performance can decrease when zoning resolution is limited or when fixed air volume operation is used. In such cases, the system may respond poorly to variable occupancy, especially under part-load conditions (Li et al. 2025). Previous studies have shown that equipment oversizing, conservative design assumptions, and limited zoning control can contribute to the gap between predicted and actual HVAC performance (Walther et al. 2025).

From an operational perspective, centralised systems are strongly influenced by control strategies governing airflow rates, supply temperatures, and scheduling (Yao et al. 2025). Advanced approaches, such as variable-speed drives and demand-controlled ventilation, can improve part-load performance. However, centralised systems can still be difficult to commission, monitor, and adapt because of their high level of integration (Kim et al. 2025; Zhou et al. 2024). To clarify the operational and performance-related characteristics discussed above, Table 2 summarises the principal strengths and limitations associated with centralised HVAC systems from a system-level perspective.

Table 2. Operational characteristics and performance-related considerations in centralised HVAC systems.

Dimension	Strengths	Potential Limitations	Performance Implications
System Capacity	Efficient service of large floor areas	-	Suitable for high-load-density buildings
IAQ Control	High levels of filtration, humidity control, and system monitoring	-	Supports stringent indoor air quality requirements
Zoning Resolution	Centralised air distribution strategies (e.g., VAV)	Reduced flexibility under limited zoning resolution	Lower adaptability to variable occupancy, particularly at part-load
Part-Load Operation	Improved when variable-speed drives and demand-controlled ventilation are implemented	Efficiency reduction in oversized or fixed-air-volume systems	Lower part-load efficiency under conservative sizing and limited zoning
Design Assumptions	Robust peak-load margins	Conservative sizing practices	Contributes to the performance gap between predicted and actual operation
Control Architecture	Central BMS for monitoring and coordination	High system-integration complexity	Commissioning and fault-detection challenges; limited adaptive operation
Operational Adaptability	Potential for advanced control strategies	Sensitivity to climatic and occupancy variations	Variation in realised operational performance

3.2. DECENTRALISED HVAC SYSTEMS

Decentralised HVAC systems distribute heating and cooling capacity directly to individual zones or rooms through unitary or semi-unitary equipment, rather than relying on a central plant serving the entire building (Zhou et al. 2024; Alabdulkarem et al. 2015). Typical decentralised HVAC configurations include split and VRF systems, alongside other modular air-conditioning units. Decentralised air-conditioning systems are frequently preferred in practice owing to their modular architecture, simplified installation, and adaptability to retrofit applications (Yau et al. 2024).

A defining feature of decentralised systems is their ability to provide zone-level thermal control (Lee et al. 2026). The independent and part-space operation capability of decentralised systems allows cooling provision to be aligned with actual usage patterns, occupancy presence, and zone-level load variations (Wang et al. 2022; Kitzberger et al. 2022; Liu et al. 2022). This operational flexibility has made decentralised systems particularly attractive in office buildings, educational facilities, and small commercial premises with variable usage patterns (Faddel et al. 2021). Despite these advantages, decentralised configurations also present inherent cons (Qian et al. 2021). In many cases, ventilation and humidity control are not intrinsically integrated within the primary cooling unit (Kim et al. 2016). As a result, fresh-air supply and latent load management may depend on separate systems or simplified control strategies. This architectural separation may increase system complexity and compromise integrated control performance, particularly in buildings located in hot and humid climates (Yau and Rajput 2022).

From a performance perspective, inverter-driven compressors and variable-speed fans have improved part-load efficiency in modern decentralised systems (Hernandez III and Fumo 2020). However, the distributed nature of multiple independent units may complicate system-wide monitoring, commissioning, and long-term performance verification (Lee and Kim 2024). Without coordinated supervision, operational degradation or control mismatches can remain undetected, contributing to discrepancies between expected and actual performance (De Wilde 2014). Overall, whilst decentralised HVAC systems offer flexibility and ease of deployment, their effectiveness depends strongly on appropriate integration with ventilation strategies and careful consideration of humidity control and operational management. A comparative synthesis of centralised and decentralised HVAC systems is presented in Table 3.

Table 3. Comparative overview of centralised and decentralised HVAC systems.

Criterion	Centralised HVAC Systems	Decentralised HVAC Systems
System Architecture	Central plant (chiller/boiler/AHU) serving multiple zones via ducted or hydronic distribution	Multiple independent unitary or multi-split systems serving individual zones
Zoning Capability	Moderate (VAV allows zonal control and CAV is limited)	High (independent indoor unit control; zone-level modulation)
Part-Load Performance	May decrease under low-load conditions if not variable-speed equipped	Typically, high due to inverter-driven compressors and variable-speed fans
Ventilation Integration	Outdoor air often intrinsically handled by the central AHU	Ventilation frequently decoupled; may require separate DOAS
Humidity Control	Central latent load management via AHU and dehumidification	Dependent on system configuration; latent load control may require auxiliary strategies
Monitoring & Control	Centralised BMS facilitates unified supervision	Distributed architecture may require advanced monitoring and FDD strategies
Commissioning Complexity	Commissioning concentrated at the plant level	Multiple units increase commissioning and performance verification complexity
Retrofit Suitability	Moderate; structural ductwork constraints	High; modular configuration allows phased installation
Initial Cost Structure	Higher plant investment, economies of scale in large buildings	Scalable; cost increases with the number of independent units
Typical Applications	Hospitals, large commercial complexes, and institutional buildings	Offices, educational buildings, retail units, retrofit projects

3.3. SYSTEM INTEGRATION AND PERFORMANCE IMPLICATIONS

Whilst centralised and decentralised HVAC configurations differ structurally, their real-world performance is increasingly shaped by the degree of system integration and control coordination rather than architecture alone (Zou et al. 2019). Contemporary building applications increasingly adopt hybrid HVAC architectures that decouple sensible and latent loads, incorporate variable-speed components, and implement coordinated supervisory control strategies to enhance energy efficiency and indoor environmental quality (Fan et al. 2023; Nawaz and Gluesenkamp 2018). In such contexts, architectural flexibility must be balanced against ventilation robustness, humidity regulation, and long-term operational stability (Rashid et al. 2025). Consequently, system effectiveness is not solely determined by nominal efficiency ratings, but by how coherently design intent, control logic, and climatic responsiveness are aligned throughout the building lifecycle (Pappalardo and Reverdy 2020). This perspective underscores the demand so as to examine HVAC performance beyond static typologies, moving toward an integrated evaluation of design-operation coupling mechanisms (Saloux et al. 2023). The interrelationship between system configuration, operational strategies, and performance outcomes is conceptually illustrated in Figure 2.

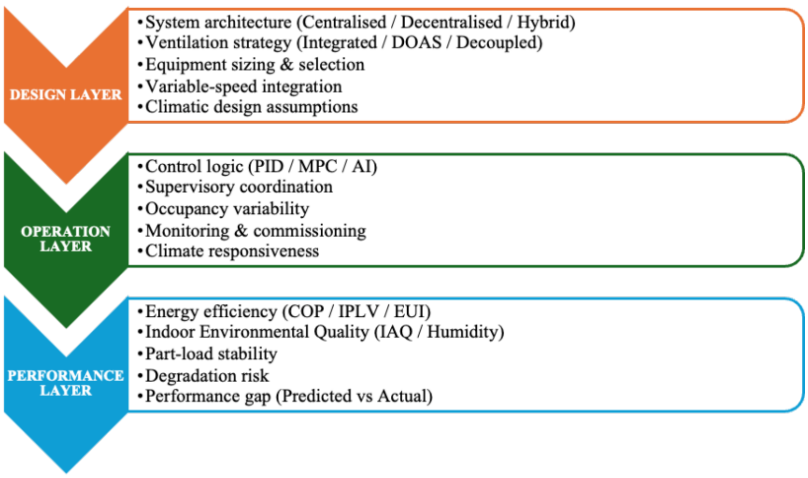

Figure 2. Design-operation-performance coupling framework in contemporary HVAC systems.

Building upon this classification and integration perspective, the following section examines the operational strategies and control approaches that shape HVAC performance in practice.

4. OPERATIONAL STRATEGIES AND CONTROL-ORIENTED PERFORMANCE DRIVERS

While Section 3 has examined system typologies from a structural design perspective, the present section evaluates how those design choices interact with operational dynamics to shape realised performance. The structural classification of HVAC systems provides an essential foundation for understanding their architectural differences. However, system typology alone does not determine real-world performance (Shi et al. 2019). In practice, the operational behaviour of HVAC installations governed by control logic, occupancy dynamics, climatic variability, and supervisory coordination plays a decisive role in shaping both energy consumption and indoor environmental quality outcomes (Van Dronkelaar et al. 2016). Contemporary buildings rarely operate under steady-state conditions; instead, they experience highly transient load profiles driven by fluctuating internal gains, variable ventilation demands and changing weather patterns (Capizzi et al. 2017). Accordingly, the effectiveness of modern HVAC systems must be examined not only in terms of operational strategy and adaptive control, but also through the lens of part-load thermodynamic behaviour, load-composition variability, and cross-layer coordination. This perspective reflects the design-operation-performance coupling framework introduced earlier and provides the analytical basis for the following subsections.

4.1. DYNAMIC LOAD BEHAVIOUR AND PART-LOAD THERMODYNAMIC IMPLICATIONS

In practical applications, HVAC systems operate predominantly under part-load conditions rather than at their rated design capacity (Huang et al. 2015). This operational reality arises from the inherently dynamic nature of building thermal loads, which fluctuate in response to occupancy patterns, internal heat gains, ventilation requirements, and climatic variability (Castaldo and Pisello 2018). Consequently, system performance cannot be adequately characterised by nominal full-load efficiency metrics alone (Crespi et al. 2022). Under part-load operation, several thermodynamic mechanisms contribute to deviations between rated and realised efficiency (Anjomshoaa and Salmanzadeh 2018). First, compressor cycling introduces transient losses associated with start-up phases, refrigerant pressure stabilisation, and incomplete heat exchanger utilisation (Agharid et al. 2025). In systems lacking modulation capability, repeated on-off cycling increases specific energy consumption and diminishes effective seasonal performance (Agharid et al. 2025). Second, oversizing, often implemented as a conservative design practice, is able to exacerbate short-cycling behaviour, further widening the gap between predicted and actual efficiency (Woradechjumroen et al. 2014). Variable-speed technologies, including inverter-driven compressors and electronically commutated fan motors, have significantly improved part-load performance by enabling continuous capacity modulation and load matching (Mahmoudi et al. 2021). By maintaining stable evaporating and condensing conditions across a broader operational envelope, such systems reduce cycling losses and improve seasonal efficiency indices (Xia et al. 2021). However, these gains are contingent upon appropriate control tuning and supervisory coordination (Homod 2018). In the absence of coherent control logic, the theoretical advantages of modulation may not fully translate into operational savings (Vakiloroaya et al. 2014).

Moreover, part-load thermodynamics cannot be considered independently of ventilation strategy and latent load management (Ma et al. 2024). In humid climates, latent loads may dominate during low sensible load periods, challenging systems that prioritise sensible capacity modulation (Liang et al. 2022). This interaction underscores the importance of integrated evaluation frameworks that couple system architecture with control strategy and climatic responsiveness (Homod 2018). Hence, from a performance assessment side, effective HVAC evaluation has to extend beyond rated COP values and incorporate dynamic load behaviour, cycling characteristics, modulation stability, and system-level coordination (Alves et al. 2016). These factors collectively determine whether nominal efficiency potential is realised in operational practice (Seo et al. 2026). The degradation mechanisms discussed above do not operate in isolation but emerge across multiple hierarchical layers of HVAC system design and operation. To synthesise these interactions, Table 4 categorises the principal factors influencing the realisation of nominal efficiency under part-load conditions.

Table 4. Mechanisms influencing the realisation of nominal HVAC efficiency under part-load conditions.

Mechanism	System Layer	Dominant Trigger	Impact on Realised Efficiency	Key Literature
Compressor cycling	Component-level	On-off control at low PLR	Transient COP degradation	(Agharid et al. 2025)
Oversizing	Design-level	Conservative peak-load sizing	Reduced run-time fraction & increased cycling	(Woradechjumroen et al. 2014)
Limited turndown ratio	Equipment-level	Minimum inverter frequency constraint	Instability & part-load inefficiency	(Xia et al. 2021)
Control misalignmen t	Control-level	Poor supervisory coordination	Energy penalty & control drift	(Su et al. 2021)
Latent load dominance	Climate/system-level	High humidity ratio under low sensible load	Increased dehumidification energy demand	(Chua et al. 2008; Kone and Fumo 2020; Yang et al. 2020a)

4.2. SENSIBLE-LATENT LOAD INTERACTION AND VENTILATION COUPLING

While Section 4.1 examined equipment-level thermodynamic degradation under part-load conditions, the realised operating envelope of HVAC systems is further reshaped by load composition and ventilation strategy. In practice, cooling demand is not a homogeneous scalar quantity but a composite of sensible and latent components whose relative proportions vary with climate, occupancy, and outdoor air requirements. In humid and mixed climates, latent loads may constitute a substantial fraction of total cooling demand, particularly during periods of reduced sensible load (Cao et al. 2025). Under such conditions, the sensible heat ratio (SHR) decreases, and moisture removal requirements persist even when temperature-driven cooling intensity declines (Chua et al. 2008). This decoupling between sensible demand and latent persistence alters evaporator operating temperature and compressor lift, thereby affecting system COP and operating envelope (Thu et al. 2018). This transition from sensible-dominant to latent-dominant operation fundamentally reshapes the effective thermodynamic operating envelope of HVAC systems. As conceptually illustrated in Figure 3, persistent latent demand forces operation at lower evaporator temperatures and higher compressor lift even when sensible cooling requirements are reduced. As a result, extended runtimes and moisture-driven operation led to a progressive degradation of realised efficiency that is not captured by temperature-based performance metrics alone.

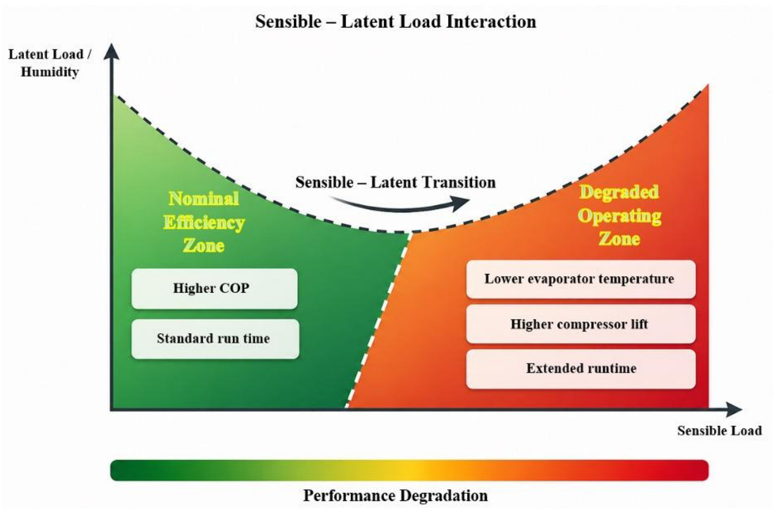

Figure 3. Conceptual illustration of sensible-latent load interaction and its influence on realised HVAC performance under part-load conditions.

Systems primarily designed around sensible capacity modulation may encounter efficiency penalties when latent control becomes the governing constraint (Winkler et al. 2019). Variable-speed compressors can reduce cooling capacity at part load; however, effective humidity control relies on extended runtimes and sustained low coil temperatures to maintain adequate latent removal (Kone and Fumo 2020). Consequently, modulation strategies optimised for temperature tracking alone may not minimise energy use under moisture-dominant scenarios. Ventilation coupling further amplifies the sensible-latent imbalance (Safdari et al. 2024). Outdoor air introduction, whether constant-volume or demand-controlled, directly increases latent cooling requirements in humid climates (Yang et al. 2020a). Elevated ventilation rates can therefore shift system operation away from optimal part-load thermodynamic conditions by increasing total enthalpy removal demands (Sekartaji et al. 2023). In decentralised or split configurations lacking dedicated outdoor air management, humidity control may rely on extended compressor operation or lower evaporating temperatures, increasing specific energy consumption (Chen et al. 2018).

Hybrid configurations incorporating DOAS attempt to mitigate this imbalance by decoupling latent and sensible loads (Mohammed et al. 2026). When properly coordinated, such architectures can stabilise part-load operation by decoupling latent and sensible control loops, thereby reducing compressor cycling frequency and improving humidity regulation stability (Cheng et al. 2023). However, the benefits of decoupling depend critically on airflow balancing, control synchronisation, and accurate humidity sensing (Li and Wang 2022). Poor integration may simply redistribute inefficiencies rather than eliminate them. These observations suggest that part-load thermodynamics cannot be assessed independently of load composition and ventilation strategy (Alves et al. 2016). Climatic humidity, occupancy-driven ventilation variation, and sensible-latent coupling collectively redefine the operating boundaries within which modulation and control strategy's function (Yang et al. 2020b). Therefore, performance assessment methodologies must explicitly account for load composition variability rather than treating cooling demand as a purely temperature-driven parameter (Liu et al. 2021). The multi-dimensional implications of sensible-latent load variability and ventilation coupling on realised HVAC efficiency are synthesised in Table 5.

Table 5. Sensible-latent load interaction and ventilation coupling system-level implications for realised HVAC performance.

Operating Context	Load Composition Behaviour	Thermodynamic Consequence	Operational Constraint	Implication for Realised Performance
Sensible-dominant cooling periods	High SHR; temperature-driven demand	Stable evaporating temperature; moderate compressor lift	Capacity modulation primarily temperature-based	Nominal efficiency more likely to be maintained under stable part-load operation
Latent-dominant cooling periods (humid climates)	Decreasing SHR; persistent moisture removal demand	Lower evaporator coil temperature; increased compressor lift	An extended runtime required for dehumidification	Reduction in realised COP despite reduced sensible demand
Reduced sensible load with sustained humidity	Decoupling between temperature and moisture demand	Coil operation governed by latent requirement	Temperature tracking alone insufficient for energy minimisation	Efficiency penalties under moisture-driven operation
Increased ventilation rates (constant or demand-controlled)	Outdoor humidity ratio increases total latent load	Increased enthalpy removal requirement	Elevated compressor lift and airflow energy demand	Shift away from optimal part-load thermodynamic envelope
Hybrid DOAS or decoupled architectures	Separation of sensible and latent control loops	Stabilised evaporator conditions when properly coordinated	Requires airflow balancing and supervisory synchronisation	Potential improvement in seasonal stability, contingent on control coherence

4.3. CONTROL ARCHITECTURE, SUPERVISORY COORDINATION AND PERFORMANCE REALISATION

Building on the thermodynamic degradation mechanisms discussed in Section 4.1 and the sensible–latent and ventilation coupling effects examined in Section 4.2, this subsection focuses on the control layer that converts these physical constraints into operational outcomes. Control architecture determines whether design intent and part-load capability are achieved in real operation. Although thermodynamic behaviour and load composition define the physical limits of HVAC systems, the conversion of theoretical efficiency into actual performance is largely a control-related issue (Mikhail et al. 2023). Modern HVAC systems operate through multi-layered control structures. These include local equipment modulation, zone-level feedback, ventilation management, and supervisory optimisation (Raman et al. 2021). Figure 4 illustrates this hierarchy and shows how coordination problems can emerge across equipment-level, zone-level, and supervisory control layers. These layers are also affected by external drivers such as weather conditions and occupancy patterns. As a result, several points of misalignment can reduce realised performance. The degree of coordination across these layers determines whether nominal efficiency values can be achieved in practice (Kim et al. 2017). In well-integrated systems, compressor speed regulation, fan modulation, airflow balancing, and humidity control operate coherently under supervisory guidance (Chuang et al. 2019). However, in many real installations, misalignment between control layers leads to inefficiencies that are not visible in rated performance values (Du et al. 2016). Communication delays, inconsistent sampling intervals, sensor bias, and conflicting setpoint hierarchies may induce unstable modulation behaviour, unnecessary compressor ramping, or excessive ventilation delivery under part-load conditions (Su et al. 2021). These effects collectively contribute to seasonal efficiency degradation without altering equipment-level specifications (Firdaus et al. 2023).

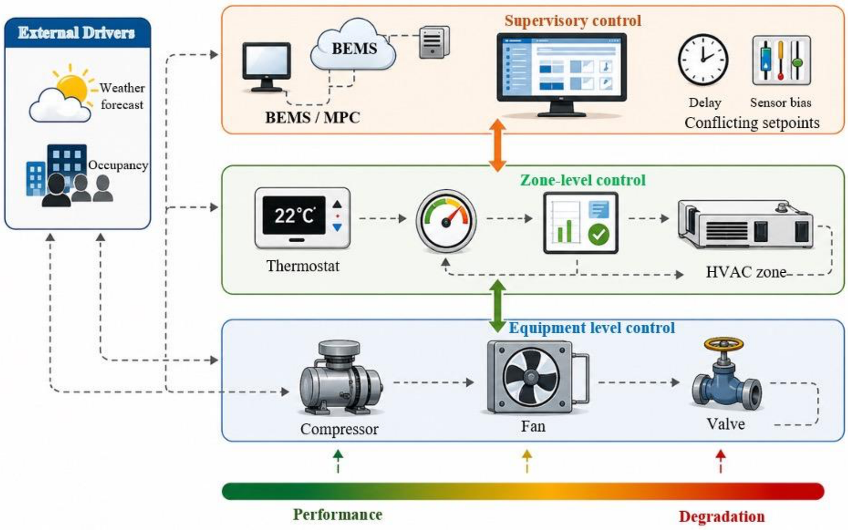

Figure 4. Schematic representation of hierarchical HVAC control architecture and coordination-related performance degradation pathways.

Coordination becomes more difficult in hybrid systems or in systems where sensible and latent cooling are handled separately. In these configurations, temperature and humidity are controlled through partly coupled processes with different sensible heat ratio characteristics (Gluesenkamp and Nawaz 2021). Poor supervisory coordination can affect condenser water control, compressor loading sequences, and cycling behaviour. This may increase effective lift or keep the system operating in low-efficiency states for longer periods (Geister and Thompson 2009; Wu et al. 2021; Rafati et al. 2022). Therefore, the theoretical benefits of load decoupling may be reduced if control coordination is poor. Recent advances in distributed and predictive control strategies attempt to address these issues by embedding system-level awareness into supervisory decision-making (Jiang et al. 2016). MPC, optimisation-based scheduling, and multi-agent frameworks integrate thermal inertia, occupancy variability, and ventilation constraints into forward-looking modulation strategies (Kim et al. 2022; Jiang et al. 2016). Unlike conventional reactive loops, these approaches anticipate load evolution and reduce short-cycling tendencies (Kim et al. 2022; Taheri et al. 2024; Raman et al. 2021). Nevertheless, their effectiveness remains contingent upon sensor fidelity, computational robustness, and practical commissioning quality (Kim et al. 2022; Zhou et al. 2024; De Wilde 2014). The recurring performance gap observed between design-stage simulations and field-measured operation underscores the centrality of control architecture. Efficiency realisation is not solely a function of component technology but of how effectively modulation strategies are coordinated across the entire system hierarchy. Consequently, control architecture should be regarded not as an implementation detail but as a defining determinant of operational performance in contemporary HVAC systems.

5. FROM NOMINAL RATINGS TO REALISED PERFORMANCE: A SYSTEM-LEVEL EVALUATION PERSPECTIVE

5.1 WHY NOMINAL EFFICIENCY METRICS FAIL UNDER DYNAMIC OPERATING CONDITIONS

Conventional HVAC performance assessment has historically relied on steady-state indicators such as rated COP, EER, and seasonal indices including SEER, SCOP, and IPLV (Erginer and Aydoğdu 2025). While these metrics provide standardised benchmarks for equipment comparison, they are inherently derived under controlled boundary conditions characterised by fixed inlet temperatures, prescribed airflow rates, and simplified load assumptions (Göbel et al. 2022). In contrast, real building environments are governed by continuously varying thermal loads, humidity ratios, ventilation requirements, and occupancy patterns (Yang and Becerik-Gerber 2016). Under such dynamic conditions, HVAC systems rarely operate at rated design points (Seo and Lee 2016). Instead, they function predominantly under partial-load regimes shaped by fluctuating sensible and latent demands (Kone and Fumo 2020; Seo and Lee 2016). Seasonal indices attempt to account for part-load operation through bin methods and degradation coefficients; however, these approaches remain dependent on predefined climate distributions and simplified load weighting schemes (Alves et al. 2016; Erginer and Aydoğdu 2025; Seo and Lee 2016). They do not explicitly represent cross-layer interactions between system architecture, modulation limits, supervisory coordination, and external disturbances (Shi et al. 2019; Van Dronkelaar et al. 2016; Alves et al. 2016). Consequently, nominal efficiency ratings should be interpreted as equipment potential rather than realised building performance (Shi et al. 2019; Van Dronkelaar et al. 2016; Alves et al. 2016; Seo et al. 2026). The divergence between rated specifications and field-measured outcomes emerges not solely from component inefficiencies, but from systemic interactions that are not embedded within conventional rating methodologies (Du et al. 2016; Su et al. 2021).

5.2 CROSS-LAYER DETERMINANTS OF REALISED HVAC EFFICIENCY

Realised HVAC efficiency is the emergent outcome of interacting determinants operating across multiple hierarchical layers. These layers, previously examined in Sections 3 and 4, interact dynamically rather than independently. At the design level, system architecture, zoning resolution, and sizing strategies establish the structural boundary within which performance can occur. Conservative oversizing and limited zoning flexibility influence runtime fractions and cycling behaviour long before operational control strategies intervene. At the equipment level, modulation capability, turndown limits, and variable-speed integration govern the stability of part-load operation. Even advanced inverter-driven systems are constrained by minimum capacity thresholds and compressor lift characteristics that shape effective operating envelopes. At the operational and control levels, supervisory coordination determines whether nominal efficiency potential is translated into practice. Misaligned setpoints, delayed feedback, inconsistent sampling intervals, or ventilation over-delivery can introduce inefficiencies that are invisible in equipment ratings yet significant in seasonal energy use. At the climatic and occupancy levels, external disturbances redefine load composition. In humid climates, latent load persistence may sustain dehumidification demand even during reduced sensible cooling periods, altering evaporator conditions and compressor lift. Ventilation-induced enthalpy shifts further reshape system operation. These determinants do not act sequentially; they act simultaneously. Realised performance, therefore, reflects the degree of alignment across design intent, modulation capability, supervisory logic, and climatic responsiveness.

5.3 A SYSTEM-LEVEL EVALUATION LOGIC FOR CONTEMPORARY HVAC SYSTEMS

In light of these interactions, HVAC performance evaluation should transition from equipment-centric benchmarking toward system-level interpretative logic. Rather than asking whether a unit achieves its rated COP, assessment should examine how effectively the overall system maintains performance under dynamic load variability and cross-layer disturbances. A system-level evaluation logic may therefore consider three integrative dimensions:

1. Stability under part-load operation: the ability of the system to avoid short-cycling, modulation instability, and excessive compressor lift under reduced load conditions;

2. Robustness to load composition variability: the capacity to maintain efficiency when sensible-latent ratios shift due to humidity dominance or ventilation requirements;
3. Coordination coherence across control layers: the extent to which local and supervisory control structures operate without inducing oscillatory behaviour, unnecessary setpoint drift, or ventilation oversupply.

This reframing does not require abandoning nominal metrics; rather, it situates them within a broader interpretative structure that acknowledges multi-layer coupling. Nominal efficiency indicators remain essential reference points, but their translation into realised performance depends on systemic alignment rather than intrinsic equipment quality alone. By embedding performance evaluation within this design-operation-performance coupling perspective, HVAC assessment becomes a holistic exercise in system coherence. Such an approach is particularly relevant for contemporary low-carbon buildings, where marginal efficiency gains and demand flexibility depend on accurate representation of dynamic behaviour rather than static rating conditions.

6. IMPLICATIONS FOR DESIGN, CONTROL, AND POLICY

The preceding sections have demonstrated that realised HVAC performance is not solely determined by rated equipment efficiency but by the degree of coherence across design configuration, modulation capability, supervisory control, and climatic variability (Shi et al. 2019; Van Dronkelaar et al. 2016; Alves et al. 2016; Su et al. 2021). This observation carries direct implications for engineering practice and regulatory evaluation. From a design standpoint, HVAC system selection and sizing should be assessed beyond peak-load adequacy. Conservative oversizing, limited zoning resolution, and insufficient ventilation integration may preserve nominal compliance while predisposing systems to part-load instability and cycling-related degradation (Li et al. 2025; Agharid et al. 2025; Woradechjumroen et al. 2014). Therefore, performance-oriented design requires explicit consideration of modulation range, zoning granularity, and sensible-latent load interaction under representative operating scenarios. At the equipment and system integration level, variable-speed technologies and decoupled ventilation architectures provide substantial potential for improving part-load stability (Mahmoudi et al. 2021; Xia et al. 2021; Mohammed et al. 2026; Cheng et al. 2023). However, the effectiveness of such configurations depends on the alignment between turndown capability, airflow management, and humidity control logic (Xia et al. 2021; Homod, 2018; Li et al. 2022). Modulation potential alone does not guarantee seasonal efficiency unless supported by coherent supervisory coordination (Homod 2018; Vakiloroaya et al. 2014; Su et al. 2021).

At the operational level, commissioning and control strategy development should be regarded as primary performance determinants rather than post-installation refinements (De Wilde 2014; Shi et al. 2019; Van Dronkelaar et al. 2016). In multi-layer control environments, misalignment between local loops and supervisory optimisation may introduce oscillatory behaviour, unnecessary compressor ramping, or ventilation oversupply under partial-load conditions (Raman et al. 2021; Du et al. 2016; Su et al. 2021). Early integration of control architecture considerations into the design phase can reduce the structural origins of performance divergence. From a policy and standardisation perspective, current compliance frameworks remain largely anchored in steady-state or seasonal rating methodologies (Alves et al. 2016; Erginer and Aydoğdu, 2025). While these metrics are indispensable for comparability, they do not explicitly capture cross-layer interactions that shape realised efficiency in dynamic building environments (Shi et al. 2019; Van Dronkelaar et al. 2016; Alves et al. 2016). Expanding evaluation protocols to incorporate indicators of part-load stability, load-composition responsiveness, and supervisory coherence may improve the alignment between regulatory certification and operational outcomes. In low-carbon building contexts, incremental efficiency improvements increasingly depend on dynamic optimisation rather than equipment substitution alone (Kim et al. 2022; Taheri et al. 2024; Raman et al. 2021). Embedding a design-operation-performance coupling perspective within engineering guidelines and performance assessment practices offers a structured pathway toward narrowing the persistent gap between predicted and realised HVAC efficiency.

6.1. RENEWABLE ENERGY-INTEGRATED HVAC SYSTEMS: PERFORMANCE AND SIZING CONSIDERATIONS

The integration of renewable energy sources, like solar and wind, into HVAC systems introduces additional complexity due to supply intermittency and temporal mismatch between energy generation and building demand (Reddy et al. 2024; Wang et al. 2019). Consequently, conventional performance metrics (e.g., COP, EER, seasonal indices) remain insufficient for evaluating such systems, as they do not fully capture dynamic operational behaviour and system-level performance under real operating conditions (Alves et al. 2016; Erginer and Aydoğdu 2025).

To enable meaningful comparison between renewable-assisted and grid-interactive HVAC systems, performance evaluation should incorporate extended indicators that capture system flexibility, demand response capability, and interactions with variable energy supply conditions (Wang et al. 2019; Manz et al. 2014). These metrics reflect not only thermodynamic efficiency but also broader system-level interactions, including demand flexibility and integration with distributed energy resources (Wang et al. 2019; Schiller et al. 2020; O'Connell et al. 2020; Arteconi et al. 2019).

From a design perspective, traditional peak-load-based sizing approaches may be inadequate due to uncertainties in load prediction and the inherently dynamic nature of building operating conditions, particularly in systems influenced by variable renewable energy inputs (Huang et al. 2015; Castaldo and Pisello 2018; Alfadil et al. 2026). Instead, system sizing should incorporate load-generation matching, storage integration, and part-load adaptability, reflecting the increasing need for flexibility in building energy systems under variable and intermittent energy supply conditions (Wang et al. 2019; Elnour et al. 2024). In particular, previous studies indicate that system performance is closely influenced by the interaction between renewable energy availability and HVAC control strategies, especially in systems employing predictive or grid-responsive control approaches (Kim et al. 2022; Wang et al. 2019).

Therefore, renewable-integrated HVAC systems are increasingly evaluated within system-level frameworks that capture the interactions between energy generation, storage, control strategies, and climatic variability (Reddy et al. 2024; Elnour et al. 2024). This perspective is consistent with the need to integrate design and operational stages, as highlighted in the literature, and supports a more realistic assessment of HVAC performance in low-carbon buildings (Shi et al. 2019; Van Dronkelaar et al. 2016).

6.2. PRACTICAL IMPLICATIONS FOR HVAC SIZING BEYOND NOMINAL COP AND SEER

Conventional sizing practices frequently rely on peak sensible load estimation and nominal equipment indicators such as COP, SEER, SCOP or IPLV. While these metrics remain useful for standardised equipment comparison, they are insufficient as standalone sizing criteria under dynamic building operation. In particular, they do not fully capture part-load instability, cycling losses, latent-load persistence, supervisory control limitations or climate-dependent shifts in the effective operating envelope. Therefore, the design-operation-performance coupling perspective proposed in this review should be interpreted as a complementary sizing and selection logic rather than a direct replacement for existing standards.

Within this framework, HVAC sizing should prioritise a wider set of quantitative parameters. At the capacity level, designers should report not only peak cooling or heating capacity, but also the distribution of expected operating hours across part-load ratios, the minimum stable capacity, the turndown ratio, runtime fraction and cycling frequency. At the efficiency level, COP or SEER should be supplemented by part-load efficiency maps, seasonal performance under representative load bins and efficiency variation under reduced sensible load conditions. For humid and mixed climates, sensible-latent performance indicators should also be reported, including SHR variation, latent removal capacity, indoor relative humidity stability, coil operating temperature and the energy penalty associated with moisture-dominated operation. In addition, control-related parameters such as set-point deviation, actuator oscillation, supervisory response time, sensor tolerance and ventilation oversupply should be considered because they determine whether nominal modulation capability can be translated into stable field performance.

The expected output of such a framework is not a single replacement efficiency value, but a multi-parameter sizing profile that supports more reliable design decisions. For designers and practitioners, this profile may include:

1. Part-load performance map showing capacity and efficiency across expected operating ranges;
2. Sensible-latent load matrix indicating whether the system can maintain humidity control without excessive cooling or reheating;
3. Climate-dependent operating envelope based on outdoor temperature, humidity ratio and enthalpy;
4. Control stability assessment identifying minimum stable operating limits and potential cycling risks;

and
5. Sizing recommendation that balances peak-load adequacy with part-load stability, humidity control and supervisory coordination.

Such an approach would help avoid the common situation in which a system is correctly sized according to nominal peak-load criteria but performs inefficiently under the conditions that dominate most annual operating hours. It would also allow commissioning teams to compare design intent with measured operation by checking whether the system remains within its expected part-load, humidity and control-stability envelopes. In this sense, the proposed framework provides a practical bridge between conventional equipment-based sizing and real-performance-oriented HVAC design for low-carbon buildings.

7. CONCLUSIONS

This review has examined contemporary HVAC systems through a structured design-operation-performance coupling perspective. The analysis highlights that realised HVAC efficiency cannot be adequately interpreted through nominal equipment ratings alone but must be understood in relation to multi-layer system interactions operating under dynamic conditions. The principal conclusions may be summarised as follows:

- Nominal efficiency metrics represent equipment potential rather than guaranteed operational performance. Indicators such as COP and seasonal indices do not inherently capture part-load variability, humidity-driven behaviour, or control-layer interactions encountered in real buildings.
- The performance gap emerges from cross-layer misalignment. Oversizing at the design stage, modulation constraints at the equipment level, supervisory coordination limitations, and climatic sensible-latent variability collectively influence seasonal outcomes.
- Part-load operation is central to performance realisation. Since HVAC systems operate predominantly under partial-load regimes, cycling behaviour, turndown limits, and control coherence significantly shape realised efficiency.
- Sensible-latent load interaction alters the effective operating envelope. In humid climates, persistent latent demand may govern system behaviour even when sensible loads decrease, thereby modifying evaporator conditions and compressor lift.
- System-level coordination determines whether nominal efficiency potential is translated into field performance. Alignment between design configuration, modulation capability, supervisory logic, and climatic responsiveness is therefore essential.

Taken together, these findings highlight the importance of interpreting HVAC performance within a broader system-level context. Rather than assessing HVAC systems solely on rated efficiency values, evaluation should consider how coherently design intent, operational strategy, and environmental conditions interact throughout the building lifecycle. For contemporary low-carbon buildings, narrowing the gap between predicted and realised efficiency depends not only on technological improvement but on cross-layer alignment within dynamic operating contexts.

8. FUTURE RESEARCH DIRECTIONS

The system-level perspective developed in this review indicates that future advances in HVAC research will depend less on incremental improvements in component efficiency and more on a refined understanding of how design intent, operational control, and environmental variability interact throughout the building lifecycle. One critical direction for future work lies in the quantitative characterisation of cross-layer performance degradation mechanisms. While oversizing, part-load inefficiency, control misalignment, and humidity-related penalties have each been studied in isolation, their combined influence on realised performance remains insufficiently quantified. Future studies should therefore aim to establish causal links between early-stage design assumptions and long-term operational outcomes, using integrated simulation-measurement approaches capable of tracing how design-stage decisions propagate into seasonal energy penalties under real operating conditions.

Equally important is the development of performance evaluation methodologies that extend beyond nominal or seasonally averaged efficiency metrics. As HVAC systems operate predominantly under dynamic and part-load regimes, future research should focus on defining evaluation indicators that capture operational stability, modulation smoothness, and control-induced inefficiencies that are not reflected in conventional

COP-based metrics. Such indicators could be derived from high-resolution operational data and embedded within simulation tools, digital twins, or post-occupancy evaluation protocols, enabling performance assessments that more accurately reflect real-world behaviour. In parallel, greater attention is required to the climatic sensitivity of HVAC operation, particularly the role of sensible-latent load interaction under humid and mixed climate conditions. Future investigations should prioritise climate-responsive modelling frameworks that explicitly account for humidity dominance, ventilation-induced latent loads, and their impact on part-load thermodynamics, rather than relying on temperature-centric design assumptions.

Another promising research direction concerns the coherence of HVAC control architectures. While advanced control strategies such as model predictive control and data-driven optimisation have demonstrated strong theoretical potential, their effectiveness in practice remains constrained by control-layer coordination, sensor reliability, and commissioning quality. Future research should therefore focus on the design and validation of supervisory control hierarchies that explicitly manage interactions between local equipment loops, zone-level controllers, and building-level optimisation routines under transient conditions. Comparative field studies using identical physical systems but different control hierarchies could provide valuable insight into how coordination quality influences realised efficiency and robustness. Finally, translating system-level performance insights into design practice and regulatory frameworks represents a critical long-term research challenge. Current standards and rating methodologies remain largely decoupled from dynamic operational behaviour and cross-layer interactions. Future work should explore how design-operation-performance coupling concepts can inform the evolution of performance-based standards, commissioning protocols, and design guidelines that better align predicted efficiency with operational reality, thereby supporting more reliable pathways toward low-carbon and resilient building performance.

AUTHOR CONTRIBUTIONS

Yusuf Nadir Yilmaz: Literature review; writing – original draft; read and approved the final version of the manuscript. **Emre Alvur**: Literature review; writing – original draft; writing – review and editing; visualisation; read and approved the final version of the manuscript. **Pinar Mert Cuce**: Conceptualisation; supervision; validation; review and editing; read and approved the final version of the manuscript. **Erdem Cuce**: Conceptualisation; methodology; supervision; project administration; validation; writing – review and editing; final approval of the manuscript; read and approved the final version of the manuscript.

COMPETING INTERESTS

The authors declare that they have no competing financial or non-financial interests.

DATA ACCESSIBILITY

All data supporting the findings of this study are included within the article. Additional information may be made available by the authors upon reasonable request.

ETHICAL APPROVAL

Not applicable. This study is based exclusively on the review and analysis of published literature and did not involve human participants or animal subjects.

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