Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

A Unified Framework and Synergy Performance Index for Integrated Energy–Water–Ventilation Systems in Buildings: A Systematic Review

Ghulam Qadir
Southern Cross University
Majid Baseer
majid.baseer@unipa.it
University of Palermo
Madhar Haddad
United Arab Emirates University
Ibrahim Ali Kachalla
Builders School of Engineering Normandy

Research Article

Keywords: Sustainable development, Integrated building systems, Energy–Water–Ventilation nexus, Resource efficiency, Digital twins and interoperability, System-level optimization, Building efficiency

Posted Date: December 19th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-8387783/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

A Unified Framework and Synergy Performance Index for Integrated Energy–Water–Ventilation Systems in Buildings: A Systematic Review

Abstract

Integrated management of energy, water, and ventilation (E–W–V) systems is increasingly recognised as a critical pathway for advancing sustainable development by reducing environmental impacts, improving resource efficiency, and strengthening climate resilience in the built environment. Despite growing interest, existing research remains fragmented, with limited attention to cross-domain synergies and a lack of standardised approaches for evaluating integrated system performance. This study addresses these gaps by introducing the Unified E–W–V Integration Framework (UEVIF) and the Synergy Performance Index (SPI), which together constitute the first combined methodological tools for systematically characterising and assessing multi-domain E–W–V interactions in buildings. A PRISMA-based systematic review of 107 peer-reviewed studies published between 2015 and 2025 was conducted to identify dominant integration typologies, resource-flow interdependencies, enabling technologies, and reported performance outcomes. The proposed SPI provides a normalised metric for evaluating synergy effects across energy demand, water use, and indoor environmental performance, enabling consistent cross-study comparison and benchmarking. The reviewed evidence indicates that integrated E–W–V strategies can achieve energy-use reductions of 30–70%, water-consumption savings of 20–40%, and measurable improvements in indoor air quality across diverse building types and climatic contexts. Nevertheless, the analysis reveals persistent limitations related to empirical validation, cross-domain modelling, and the absence of unified performance metrics. By offering a transferable analytical framework and a standardised synergy indicator, this review supports evidence-based design, research, and policy interventions aimed at accelerating the transition toward climate-aligned, net-zero, and circular built environments.

Keywords: Sustainable development; Integrated building systems; Energy–Water–Ventilation nexus; Resource efficiency; Digital twins and interoperability; System-level optimization; Building efficiency

1. Introduction

The building sector is one of the most resource-intensive components of global infrastructure, responsible for nearly 40% of total energy consumption and contributing to about one-third of global greenhouse gas (GHG) emissions [1]. The challenges posed by rapid urbanization, rising expectations for indoor comfort, and increasingly stringent climate targets underscore the urgency of transitioning toward net-zero, climate-resilient building system configurations [2]. Traditionally, energy, water, and ventilation (E–W–V) subsystems have been designed and optimized independently, resulting in fragmented operations, redundant infrastructure, and missed opportunities for cross-domain synergy [3, 4]. Recent research emphasizes integrated approaches that conceptualize buildings as interconnected ecosystems rather than isolated components [5]. Integrating energy generation and storage with water reuse, distribution, and indoor air quality (IAQ) management enhances overall system

efficiency, yielding substantial performance improvements, lower carbon emissions, and improved occupant health and comfort [4, 6]. Examples include coupling photovoltaic (PV) generation with water pumping systems [7], linking greywater recovery with humidity control [8], and coordinating natural ventilation with smart HVAC scheduling [3], all of which demonstrate the potential of intelligent control and shared infrastructure to strengthen building sustainability.

Despite advancements in sustainable building design, system fragmentation remains a persistent barrier. Many studies continue to focus narrowly on single domains—energy, water, or ventilation—without examining how these systems interact when co-implemented. This siloed perspective obscures potential synergies that could enhance operational efficiency, reduce lifecycle costs, and support deeper carbon mitigation. At the same time, contemporary global policy frameworks increasingly emphasize the interconnectedness of energy efficiency, water conservation, and indoor environmental quality. These domains are now recognized as fundamental pillars of sustainable built environments. The European Union Energy Efficiency Directive (EED 2023/1791), for instance, targets an 11.7% reduction in total energy demand by 2030 through cross-sectoral system integration [9]. Similarly, the Paris Agreement promotes profound decarbonization through integrated technologies, demand-side management, and systemic resource optimization [10]. The United Nations Sustainable Development Goals (SDGs)—particularly SDG 11 on sustainable cities and SDG 13 on climate action—further reinforce the need for resource-efficient and climate-resilient infrastructure [11]. However, the building sector continues to operate largely in silos, with E–W–V systems still designed and managed independently in most contexts [12]. Integrating these systems offers a critical opportunity to align local building operations with global sustainability commitments [13], yet the precise mechanisms through which E–W–V integration can directly support such objectives remain insufficiently articulated.

A major contributing factor is the absence of a unified analytical framework capable of systematically capturing interactions across energy, water, and ventilation systems. Existing reviews tend to address only isolated components—such as hybrid ventilation, water–energy interactions, or IAQ-related ventilation performance, while overlooking the broader tri-domain interactions that determine the performance of fully integrated systems. Furthermore, many studies rely heavily on simulation-based analyses with limited empirical validation, often producing inconsistent baselines and non-standardized reporting practices. These inconsistencies hinder comparability across technologies, building types, and climatic contexts.

To address these limitations, this review introduces two methodological contributions: (i) the Unified Energy–Water–Ventilation Integration Framework (UEVIF), a structured conceptual model that organizes integration pathways, resource flows, and enabling technologies reported across the literature; and (ii) the Synergy Performance Index (SPI), the first mathematically defined and normalized metric for quantifying synergy across E–W–V domains. SPI captures both domain-specific performance gains and cross-domain interaction effects, overcoming the absence of standardized metrics for evaluating integrated building systems.

By consolidating empirical findings, simulation evidence, and hybrid modeling approaches, this review provides a structured synthesis of E–W–V integration strategies and identifies key

research gaps related to calibration, validation, techno-economic trade-offs, and circularity. This integrative perspective supports the development of climate-aligned, resilient, and resource-efficient building systems.

This review examines peer-reviewed studies published between 2015 and 2025 that investigate integrated building systems combining at least two of the three domains (energy, water, ventilation) in residential, commercial, or institutional settings. Eligible studies report quantifiable metrics such as energy savings, water conservation, carbon reduction, cost efficiency, or IAQ performance. Both simulation-based research and empirical case studies are included, whereas studies focused solely on single systems, non-building applications, or those lacking quantitative data are excluded.

2. Background

Energy systems (ES) form an essential foundation for improving building performance. For example, solar photovoltaic (PV) technology plays a crucial role in the decarbonization process [14]. The integration of PV with battery storage systems enhances reliability while addressing intermittency issues. To effectively manage non-dispatchable renewable energy sources, advanced operational strategies and predictive management frameworks are increasingly required [15]. Additionally, reliability indices have become critical tools for evaluating the performance and resilience of distributed solar energy systems [14]. Hybrid approaches—such as combining PV with electrochemical conversion (PV+EC)—offer improved system stability and performance, yet continue to face challenges related to cost, scalability, and environmental sensitivity [16, 17]. Empirical studies demonstrate significant energy savings and reductions in carbon emissions when PV systems are integrated with latent heat storage or hydrogen production systems [18]. For instance, a 3 kWp rooftop PV installation in India generated more than 4000 kWh annually, highlighting the potential of distributed solar energy to meet local demand under suitable climatic conditions [19]. However, the performance of these systems remains highly sensitive to environmental factors such as insolation and temperature [16], underscoring the need for climate-adaptive, integrated, and synergistic system designs.

In the context of this review, energy systems are also central to E–W–V integration, as they often act as the coordinating domain linking water pumping, thermal loads, and ventilation-driven energy demand. This interdependence provides a foundational pathway for the unified framework developed later in this study.

2.1 Integrated Water Systems (WS)

Water systems (WS) play a crucial role in enhancing resource efficiency, yet they are often overlooked in integration research. Greywater recycling and rainwater harvesting (RWH) reduce freshwater demand, ease pressure on municipal treatment networks, and support high-value non-potable uses [20]. When combined, these systems enhance water efficiency and reduce environmental impacts [21]. In multi-storey buildings, greywater supply frequently exceeds non-potable demand, creating opportunities for optimized storage and distribution networks [20]. Advanced treatment methods—including membrane filtration and biological processes—have significantly improved water quality for various applications [22]. Integration with urban agriculture enables closed-loop resource systems that simultaneously reduce water usage and support local food production [23]. Life-cycle assessments further show that decentralized water reuse systems can reduce both energy consumption and GHG emissions

when compared with conventional centralized networks [20]. However, challenges persist: high capital costs, operational complexity, maintenance demands, and user perceptions of greywater safety continue to limit widespread adoption [20, 21]. Climate variability also affects system performance, calling for context-specific, adaptable, and resilience-oriented design strategies [23].

Water systems are also fundamental to cross-domain synergies because water-based processes (e.g., humidity control, heat recovery, pumping schedules, and wastewater reuse) directly influence both ventilation loads and energy demand. This interaction underpins several integration pathways captured in the UEVIF framework.

2.2 Ventilation systems (VC) and HVAC Integration

Ventilation systems (VS) are essential for balancing indoor air quality (IAQ), occupant comfort, and energy use. Hybrid ventilation systems—combining natural and mechanical methods—can significantly reduce energy consumption while maintaining acceptable IAQ [24, 25, 26]. By exploiting diurnal temperature variations through night ventilation, cooling loads can be lowered, thereby reducing reliance on mechanical systems [27, 28]. System performance is further enhanced through passive envelope measures such as thermal mass, insulation, and strategic window placement, which improve natural ventilation effectiveness [28, 29]. Case studies show energy savings of up to 30% and reductions in fresh air intake exceeding 90%, while still maintaining IAQ and thermal comfort standards [24, 26]. Nevertheless, hybrid systems remain susceptible to challenges such as uneven airflow distribution and exposure to outdoor pollutants [28]. Implementing smart controls, real-time sensing, and demand-controlled ventilation (DCV) can mitigate these issues by adjusting ventilation rates based on occupancy, IAQ, and environmental conditions [25, 26]. Integrating ventilation with other building systems unlocks additional benefits. For example, coupling heat recovery ventilation with domestic hot-water systems enhances overall energy efficiency [24, 28]. Moreover, aligning HVAC operations with renewable energy production and water reuse strategies supports dynamic load balancing, higher resource efficiency, and improved system resilience [26, 30].

Ventilation systems are a key synergy driver in E–W–V integration because ventilation influences thermal loads, humidity levels, water consumption for cooling/humidification, and overall energy use. Therefore, VS integration provides some of the strongest leverage points for synergistic system-level performance improvements.

2.3 Synergistic Integration and System-Level Approaches

Significant innovation emerges when energy, water, and ventilation systems are integrated into a cohesive, data-driven, and dynamically optimized framework. Smart building management systems (BMS) and AI-driven controls enable simultaneous optimization across all three domains by adapting system operations dynamically to occupancy patterns, weather conditions, and resource availability [31, 32]. Studies suggest that such integrated control systems can reduce energy costs by up to 25% and decrease prediction errors by 18% [33]. Integrated resource systems also contribute to broader sustainability and circularity objectives. Approaches such as decentralized energy–water–waste networks, HVAC-integrated vertical farming, and district-scale energy sharing demonstrate the potential for up to 40% reductions in GHG emissions, 70% reductions in resource demand, and significant improvements in

overall system efficiency [31]. These strategies align with circular economy principles, positioning buildings as active resource hubs within urban sustainability networks.

Despite these advancements, full three-domain integration (E + W + V) remains rare. Most studies focus on dual-domain interactions—typically energy–ventilation or energy–water—while water–ventilation synergies remain particularly underexplored [31, 34]. Additionally, the majority of research is concentrated in technologically advanced regions, leaving substantial gaps in Africa, Latin America, and the Middle East, where climate vulnerability and resource scarcity increase the urgency of integrated system solutions [23, 31].

To address these limitations, this review introduces the Unified Energy–Water–Ventilation Integration Framework (UEVIF) and the Synergy Performance Index (SPI). These tools systematically categorize resource flows, quantify cross-domain performance gains, and formalize integration pathways. By synthesizing the interactions among E, V, and W subsystems, Table 1 provides the empirical foundation on which the UEVIF framework and SPI metric are constructed.

Table 1. Representative examples of (E–W–V) synergies in building systems (BS), highlighting direction of resource interactions, enabling technologies, typical applications, and performance outcomes reported in literature.

System Category	Synergy Contribution (E–V–W)	Representative Technologies / Strategies	Typical Applications	Performance / Synergy Metrics	References
Ventilation & IAQ	V → E: DCV reduces cooling/heating demand V ↔ W: Humidity control affects water use	CO_2 + PIR + VOC sensor fusion DCV Adaptive comfort setpoint control DAC module for CO_2 removal Occupancy-aware SPDI algorithm	Office buildings, classrooms, mixed-mode ventilation	Occupancy accuracy ↑ 53.4→98.3% Cooling energy ↓ 27.5% Fresh air intake ↓ 91% IAQ & comfort significantly improved	[35-37] [38, 39]
HVAC & Thermal Systems	E ↔ V: HVAC load influenced by ventilation demand E ↔ W: Heat recovery links to DHW	BMS + MOPSO optimisation TABS and radiant systems Grey-box MPC-ready models Distributed MPC for radiant floor	Commercial and residential buildings, district heating networks	EUI ↓ 34.5% Peak plant size ↓ 45% RMSE ↓ 0.24 °C Enhanced load flexibility	[40-43]
Passive Design & Envelope Optimisation	E ↔ V: Reduces HVAC and ventilation load E ↔ W: Cooling demand impacts water use	Envelope insulation optimisation Passive shading (solar exoskeleton) Double-glazing retrofits Underground thermal buffering	Residential and office buildings, retrofits	Embodied C ↓ 37–80% Energy savings 24–53% Cooling energy ↓ 30%	[44-48]

Renewable Energy & NZC Integration	E core: Supplies power to HVAC & ventilation E ↔ W: Supports water treatment & pumping	BIPV/BIPV-T façades Hybrid PV + wind + BESS MES façade with HRV/ERV CHP + TES	NZEB retrofits, off-grid buildings, campus ES	On-site generation ≈ 191 MWh CO_2 ↓ 53% Annual CO_2 reduction ≈ 44 t LCOE ↓ 8–22%	[49-54]
Water, DHW & Water–Energy Nexus	W ↔ E: DHW drives boiler and heat pump energy W ↔ V: Humidity affects ventilation	DHW design and wastewater heat recovery Hybrid SARIMA–ANN forecasting Dual-piping recycled water ML-based boiler optimisation	Residential towers, landscaping /cooling, multi-apartment housing	DHW share ≈ 32–50% total energy RMSE ↓ vs. baseline Workability ↑ 12–14% Improved demand prediction	[52, 55-58]
Smart Control, AI & Digital Intelligence	E ↔ V ↔ W: Optimises all three domains simultaneously	AI-based EMS & predictive scheduling Explainable AI for GHG estimation BIM + IoT integration 5G-enabled real-time control	Smart buildings, predictive control, retrofit projects	Energy cost ↓ 15–25% Prediction error ↓ 18% Energy savings ↑ 15–30%	[59-62]
Integrated Resource Systems & FEW Synergies	E + V + W synergy: Closed-loop coordination of energy, water, and ventilation	Decentralised energy-water-waste systems Vertical farming + HVAC synergy Value-engineered resource packages District-scale energy sharing networks	Circular resource systems, multi-building clusters	GHG ↓ 40% Demand ↓ 70% Efficiency ↑ 40% Enhanced resilience	[31] [34, 63, 64]

Note: The positions of each engineering subsystem within the broader E–W–V synergy framework illustrate how they contribute individually (e.g., ventilation reducing cooling energy demand), how they interact in dual-domain configurations (e.g., HVAC ↔ water via heat recovery loops, greywater ↔ humidity control), and how full tri-domain synergy (E + W + V) emerges through integrated control strategies, coordinated resource flows, and shared infrastructure. These positional relationships form the basis of the UEVIF model presented in this review, clarifying how different subsystems transition from isolated operation to partial integration and ultimately to fully synergistic behaviour.

Table 1 provides a consolidated summary of the integration typologies and their documented performance outcomes in recent studies. It categorizes representative E–W–V synergies according to directionality of resource flows, enabling technologies such as hybrid ventilation, greywater–HVAC coupling, or PV-assisted pumping, and the operational or climatic context in which the synergy was demonstrated. This structured typology supports the subsequent development of the UEVIF framework and informs key parameters used in the SPI formulation.

3. Methodology

A systematic review approach was employed to ensure transparency and reproducibility in the methodology. The process involved three main stages: selecting databases and identifying keywords, screening and including eligible studies, and thematic coding for both quantitative and qualitative synthesis. The review spanned the period from 2010 to 2025, focusing on peer-reviewed journal articles. Data extracted from the selected studies were systematically mapped to identify research trends, performance outcomes, and recurring knowledge gaps thereby establishing a comprehensive and comparable evidence base for integrated E–W–V systems. In this methodology, additional analytical layers were incorporated to support the development of the Unified Energy–Water–Ventilation Integration Framework (UEVIF) and the Synergy Performance Index (SPI), enabling both conceptual and quantitative synthesis.

3.1 Study Design and Protocol

This systematic review followed the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure methodological rigor, reproducibility, and transparency. The review synthesizes and critically evaluates current research on integrated energy–water–ventilation (E–W–V) systems, with emphasis on synergistic design strategies, cross-domain interactions, and performance optimization. The methodology was structured around four central research questions:

- What technological and operational approaches have been developed to integrate E–W–V systems in buildings?
- How are synergy types (spatial, temporal, and control-based) defined, characterized, and implemented?
- What measurable outcomes—such as energy savings, CO_2 reductions, IAQ improvements, and water reuse efficiency—have been documented?
- What methodological gaps, inconsistencies, and limitations exist, and how can future research advance holistic E–W–V integration?

In addition, this study incorporated a methodological synthesis step in which extracted data were used to formalize integration pathways for UEVIF and to identify empirically supported parameters necessary for SPI formulation. This enhanced alignment between evidence extraction and methodological innovation strengthens the contribution of the review beyond descriptive synthesis.

This framework situates the review within broader discourses on building decarbonization, circular resource management, and climate-resilient design, enabling a multi-dimensional analysis that moves beyond traditional siloed approaches.

3.2 Search Strategy

A comprehensive literature search was conducted using Scopus, Engineering Village, and Web of Science databases for the period 2015–2025. Boolean operators and targeted keyword combinations ensured both breadth and precision:

("energy–water–ventilation" OR "E–W–V integration" OR "building system synergy" OR "multi-energy systems" OR "smart buildings") AND ("energy efficiency" OR "water reuse" OR "ventilation" OR "indoor air quality" OR "net-zero buildings")

Database-specific records retrieved were as follows:

-Scopus: 802

-Engineering Village: 25
-Web of Science: 956

All records were imported into EndNote for duplication removal and screening management. The final search update was conducted in November 2025 to ensure inclusion of the most recent advancements in integrated building systems. Additional manual searches of key authors and citation networks were also performed to capture studies frequently referenced in E–W–V integration research but not indexed through keyword queries.

3.3 Inclusion criteria

Studies were eligible for inclusion if they met the following criteria:

- Peer-reviewed journal articles (2015–2025), written in English
- Addressed at least two of the three domains: energy, water, ventilation
- Reported quantifiable performance metrics (energy/water savings, CO_2 reduction, IAQ, cost)
- Focused on building-scale systems (residential, commercial, or institutional)
- Included simulation-based, empirical, or mixed-method research

These criteria ensured that the resulting dataset contained comparable, measurable, and methodologically transparent studies relevant to integrated system analysis. Furthermore, selected studies needed to contain sufficient technical detail to support the reconstruction of integration pathways for UEVIF and to extract performance parameters relevant for SPI demonstration.

3.4 Exclusion criteria:

Studies were excluded if they:

- Focused solely on one domain (e.g., standalone HVAC, PV, or water reuse)
- Addressed non-building applications (e.g., district utilities, industrial water treatment)
- Consisted of editorials, commentaries, conference abstracts, or grey literature—unless issued by authoritative bodies (e.g., IEA, UNEP)
- Lacked methodological transparency or quantifiable performance data

These exclusions helped maintain analytical integrity and applicability to building-scale E–W–V integration. Excluding studies without measurable data was essential to support the SPI's requirement for baseline and integrated performance metrics.

3.5 Screening process

In accordance with the PRISMA 2020 framework, an initial total of 1,783 records were retrieved. After eliminating 544 duplicates, 1,239 records underwent screening by title and abstract. Subsequently, a full-text assessment of 327 reports was conducted, resulting in 107 studies meeting the inclusion criteria and being incorporated into the final synthesis.

The selection process is summarized in Figure 1 (PRISMA flow diagram), which illustrates each stage of identification, screening, eligibility assessment, and final inclusion. During full-text evaluation, additional coding tags were assigned to classify each study's integration type, enabling technology, validation method, and synergy potential. These tags were later synthesized into the UEVIF taxonomy and SPI analytical structure.

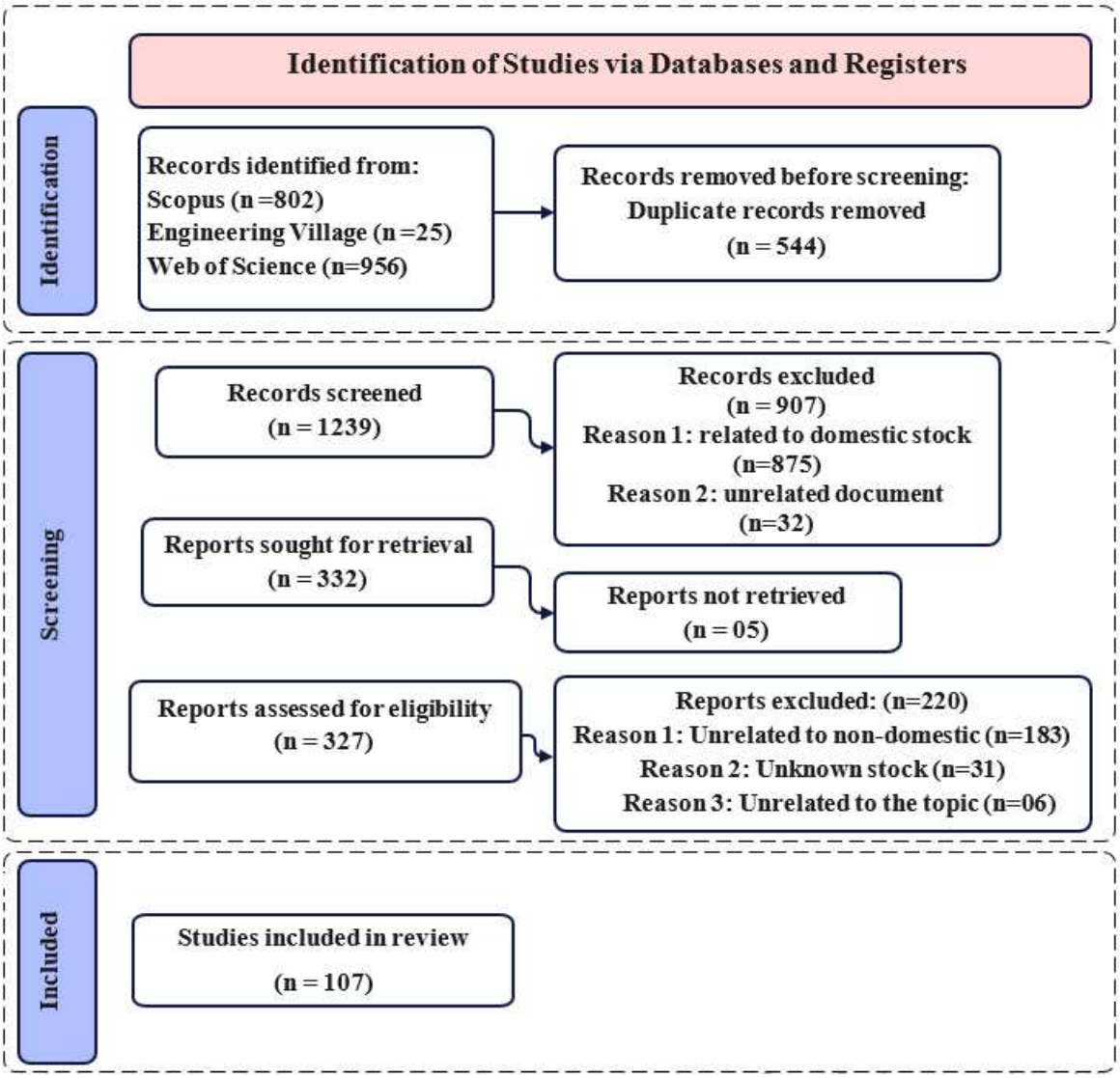

Figure 1. PRISMA flow diagram illustrating the reference selection process for this study.

3.6 Data Extraction and Coding

Data extraction was performed independently by two reviewers, followed by cross-verification to minimize bias. Each included study was coded according to the following categories:

3.6.1 Bibliographic information: authors, year, journal, region

3.6.2 System domains: energy, water, ventilation

3.6.3 Integration typology: passive, hybrid, renewable-coupled, AI-driven smart control

3.6.4 Technological strategy: BIPV/T façades, greywater heat recovery, demand-controlled ventilation, predictive energy management, etc.

3.6.5 Performance indicators: energy and water savings (%), CO_2 reduction, IAQ improvements, life-cycle cost data

3.6.6 Methodological approach: simulation, case study, experimental, or mixed-method

In this revised analysis, additional coding tags were introduced to support the development of the Unified Energy–Water–Ventilation Integration Framework (UEVIF). These included: (i) directionality of resource flows (e.g., energy → ventilation, water ↔ ventilation), (ii) degree

of integration (single-domain, dual-domain, full tri-domain), and (iii) suitability for Synergy Performance Index (SPI) calculation based on reported baseline and integrated performance metrics.

This expanded coding scheme enables structured comparison across studies and ensures that extracted data directly contribute to both conceptual (UEVIF) and quantitative (SPI) components of the review.

3.7 Analytical Framework

The analysis combined thematic synthesis with quantitative cross-comparison, structured around five analytical dimensions:

3.7.1. Integration Typologies: Classification of E–V, E–W, and E–W–V synergies.

3.7.2. Performance Evaluation: Comparison of performance outcomes (energy, water, CO_2, IAQ).

3.7.3. Technological Evolution: Mapping transitions from passive/hybrid systems to AI-enabled, BMS-integrated infrastructures.

3.7.4. Validation and Benchmarking: Assessment of simulation robustness and empirical validation.

3.7.5. Research Gaps: Identification of limitations and future research pathways toward circular, net-zero building systems.

These dimensions collectively enabled a multi-layered synthesis bridging technical, operational, and policy perspectives.

Additionally, extracted performance metrics were analyzed to establish the empirical basis for SPI formulation, allowing synergy patterns to be translated into a normalized performance index. UEVIF was constructed by synthesizing coded integration pathways, resource interactions, and enabling technologies across the selected studies, resulting in a unified conceptual structure for tri-domain integration.

This dual analytical approach—conceptual via UEVIF and quantitative via SPI—ensures that the review not only categorizes existing knowledge but also generates methodological tools for future evaluation and system design.

3.8 Synergy Performance Index (SPI)

To provide a consistent and comparable method for evaluating multi-domain integration across energy, water, and ventilation systems, this review introduces the Synergy Performance Index (SPI). The SPI offers a unified metric that distinguishes true synergy from merely additive improvements by quantifying the joint performance enhancement achieved when E–W–V subsystems operate in an integrated manner.

3.8.1. Baseline and Integrated Performance Metrics

Performance indicators were extracted for each study across three domains:

- Energy (E): energy consumption, renewable generation, thermal efficiency
- Water (W): potable water reduction, greywater reuse, water recovery efficiency
- Ventilation (V): IAQ improvement, pollution removal efficiency, humidity control

Let:

- Baseline performance: E_0, W_0, V_0
- Integrated performance: E_i, W_i, V_i

Performance improvements are expressed as:

$$\Delta E = \frac{E_0 - E_i}{E_0}, \Delta W = \frac{W_0 - W_i}{W_0}, \Delta V = \frac{V_i - V_0}{V_0}$$

3.8.2. Normalization and Weighting

To ensure comparability across heterogeneous metrics, each improvement is normalized as:

$$\Delta E_n = \frac{\Delta E}{\Delta E_{\max}}, \Delta W_n = \frac{\Delta W}{\Delta W_{\max}}, \Delta V_n = \frac{\Delta V}{\Delta V_{\max}}$$

Weighting factors allow flexibility according to project priorities:

$$w_E + w_W + w_V = 1$$

3.8.3. SPI Mathematical Formulation

The Synergy Performance Index (SPI) is defined as:

$$SPI = (w_E \Delta E_n + w_W \Delta W_n + w_V \Delta V_n) \times (1 + S_f)$$

where the Synergy Factor (Sf) captures interaction effects beyond individual-domain improvements:

$$S_f = \frac{\Delta E_n \cdot \Delta W_n + \Delta E_n \cdot \Delta V_n + \Delta W_n \cdot \Delta V_n}{3}$$

- $S_f = 0$: purely additive behavior
- $S_f > 0$: positive synergy
- $S_f < 0$: trade-offs or negative interaction

3.8.4. Interpretation of SPI

SPI Range	Interpretation
0.0–0.3	No or weak synergy
0.3–0.6	Moderate synergy
0.6–1.0	High synergy

This review introduces SPI as a methodological framework; numerical SPI calculations are not performed because the included studies report heterogeneous metrics that prevent standardized quantitative evaluation. Future empirical studies may apply this formulation when compatible datasets become available.

To contextualize the proposed Synergy Performance Index within an integrated system architecture, the Unified Energy–Water–Ventilation Integration Framework (UEVIF) is presented in Figure 2.

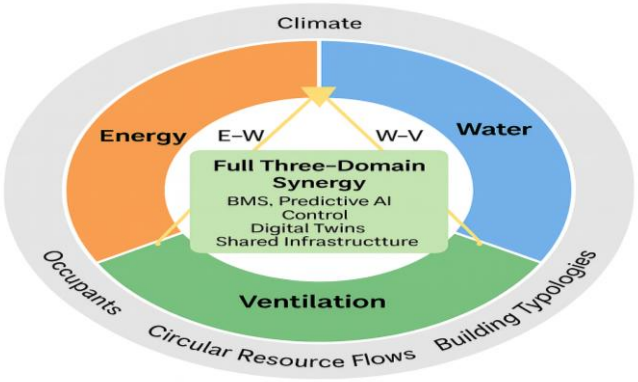

Figure 2. Unified Energy–Water–Ventilation Integration Framework (UEVIF)

The framework distinguishes between single-domain operation, dual-domain coupling, and full tri-domain synergy, emphasizing that meaningful performance gains emerge only when interactions across energy, water, and ventilation systems are jointly optimized.

In this context, predictive AI control refers to data-driven forecasting and optimization methods—such as machine learning models and model predictive control (MPC)—that anticipate future energy demand, water use, and indoor environmental conditions based on historical data, occupancy patterns, and climatic inputs. These predictive capabilities enable proactive system coordination rather than reactive control, thereby enhancing efficiency, resilience, and indoor environmental quality.

By explicitly accounting for external influences—including occupants, building typologies, circular resource flows, and climate—the UEVIF highlights the importance of context-aware integration and provides a transferable conceptual foundation for evaluating integrated building systems across diverse applications.

3.9 Limitations

While this review is comprehensive, it is subject to several limitations. Restricting the search to English-language publications may have excluded relevant international studies. Limited access to proprietary or industrial datasets may have resulted in underrepresentation of large-scale real-world implementations. Additionally, variability in data reporting and the prevalence of simulation-based studies limited the feasibility of a full meta-analysis, necessitating a combined qualitative–quantitative synthesis approach.

A further limitation relates to incomplete reporting of baseline and integrated system metrics in many studies, which constrained the number of cases suitable for SPI demonstration. Variability in technological maturity, climatic contexts, and control strategies also introduced heterogeneity that limits direct comparison across all study types. Despite this, the standardized coding and analytical structure mitigated these challenges by ensuring transparent categorization of all evidence.

Despite these limitations, the review provides the first consolidated methodological framework for evaluating E–W–V synergies, effectively bridging disciplinary gaps and supporting evidence-based strategies for climate-resilient, net-zero-ready buildings. The introduction of UEVIF and SPI further strengthens the methodological contribution by offering reproducible tools for future research and practical implementation.

4. Results and Discussion

This section presents the key findings from the review of E–W–V integration studies published between 2010 and 2025. The results are organized into three stages. First, a quantitative overview highlights research trends based on system focus, geographic region, and methodological approach. Second, representative examples demonstrate how different synergy types operate within real building contexts. Finally, a thematic synthesis traces the evolution of research over time, identifying persistent gaps, emerging directions, and priorities for future investigation. These findings also provide the empirical evidence base for developing the Unified Energy–Water–Ventilation Integration Framework (UEVIF) and informing parameter selection for the Synergy Performance Index (SPI).

4.1 Word Cloud/Thematic analysis



Figure 3. Word cloud generated using Voyant Tools from keywords, titles, and abstracts of reviewed literature on integrated building systems.

A word cloud was generated using Voyant Tools (Figure 3) based on keywords, titles, and abstracts from the reviewed literature. The frequency of terms such as *building/buildings* (78 occurrences), *energy* (46), *systems/system* (44), and *integrated/integration* (25) clearly reflects the field's shift from isolated system optimization toward more holistic, multi-domain frameworks [65, 66]. This progression highlights the growing recognition that building performance cannot be understood in single-resource silos, but must instead be addressed through interconnected, system-of-systems approaches that link energy, water, and environmental control subsystems [67, 68].

The prominence of terms such as *thermal*, *comfort*, and *natural ventilation* (each occurring roughly 11–12 times) indicates an increasing emphasis on occupant well-being as a core design and operational objective, alongside energy efficiency [69, 70]. Meanwhile, emerging terms such as *hybrid*, *prediction*, and *smart* underscore the rapid adoption of data-driven, AI-

enhanced control strategies that enable more adaptive and responsive building operation [32]. Notably, while *carbon* (14) and *ventilation* (12) appear frequently, the relatively modest occurrence of *water* (11) and *reuse* highlights a critical research imbalance, suggesting that water-related integration remains underexplored compared to energy and ventilation. This gap presents an opportunity for future work to advance resource-nexus methodologies that incorporate water efficiency, reuse, and treatment more prominently within integrated frameworks [23].

This thematic pattern mirrors the quantitative evidence from coded studies, where dual-domain E–V and E–W configurations were far more common than full tri-domain (E–W–V) integrations, reinforcing the need for a unifying framework such as UEVIF.

4.2 Evolution of research

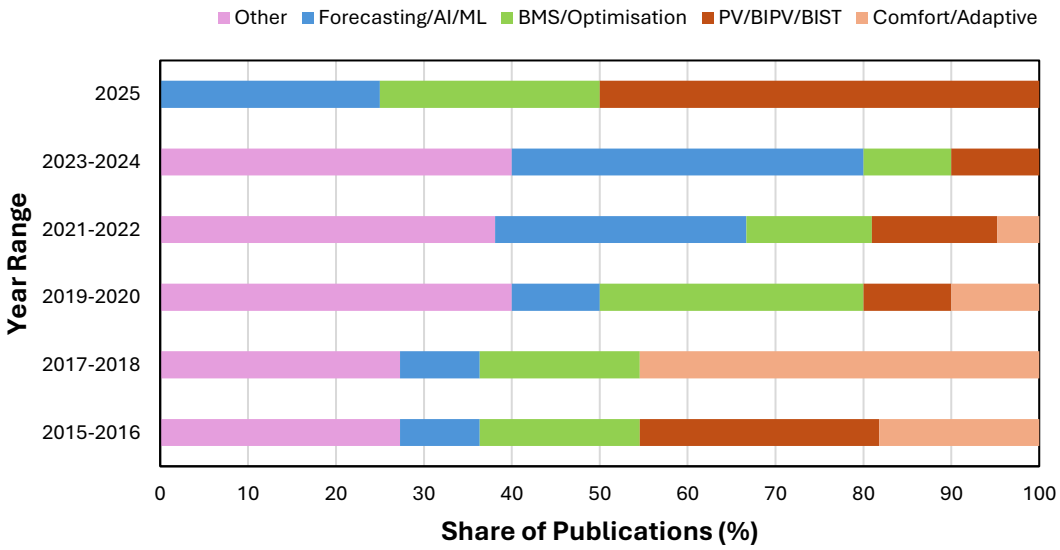

Figure 4. Illustrates the shifting research landscape of building-level E–W–V studies over the past decade (2015–2025), revealing four distinct phases in thematic progression.

Phase 1 (2015–2018): Passive and Envelope-Dominant Approaches

Early studies focused primarily on passive design strategies, envelope optimization, and static control mechanisms aimed at enhancing thermal comfort and reducing operational energy demand [36, 71-73]. These approaches relied heavily on rule-based setpoints, natural ventilation, and early life-cycle CO_2 analyses, reflecting a period characterized by incremental efficiency gains rather than integrated system design.

Synergies during this phase were limited and unidirectional (e.g., envelope → energy), with minimal explicit interaction across water or ventilation domains.

Phase 2 (2018–2020): Policy-Driven Simulation and LCA Integration

Increasing global policy commitments—including the EU's 2030 framework and early national net-zero pledges—triggered a surge in studies that combined Building Information Modelling (BIM), life-cycle assessment (LCA), and multi-objective simulation frameworks. Research during this period emphasized design-stage decision support tools that aligned building projects with emerging carbon budgets and regulatory targets [44, 74, 75]. At the same

time, methodological innovations such as calibrated building models and grey-box approaches helped narrow the gap between simulation and real-world performance [60, 76].

This period marks the emergence of dual-domain analyses (E–V and E–W), although integration remained largely conceptual and control strategies were not yet coordinated across subsystems.

Phase 3 (2021–2023): Rise of AI, Machine Learning, and Predictive Optimization

Driven by rapid advancements in IoT, real-time sensing, and cloud computing, the period from 2021 to 2023 saw substantial growth in AI/ML-based forecasting, model predictive control (MPC), and data-driven optimization [50, 51, 77]. These innovations coincided with increased policy pressure following COP26 (2021) and the global mainstreaming of net-zero energy/carbon building standards [78, 79]. Studies during this phase increasingly integrated hybrid renewable systems (PV, storage, thermal buffering) within unified operational and control frameworks [51, 80].

For the first time, dynamic cross-domain interactions were explicitly modelled, forming the scientific basis for tri-domain integration—but most studies still lacked standardized synergy indicators, highlighting the need for SPI.

Phase 4 (2024–2025): Toward Comprehensive Nexus Integration

The most recent studies expanded beyond energy-centered approaches to include water–energy nexus strategies, such as hot-water forecasting, recycled water reuse, and building-scale circular retrofits [52, 55, 81, 82]. This period marks a transition toward integrated, intelligence-enabled, policy-aligned building operations that incorporate carbon, water, and energy within unified, lifecycle-based decision-making frameworks [61, 83].

Several studies in this phase demonstrated early examples of full E–W–V integration, enabled by smart BMS platforms, integrated heat recovery, and digital twin–based optimization workflows. These studies represent foundational evidence used in constructing the UEVIF model.

Collectively, the evolution of research highlights a shift from component-level optimization to system-level integration, emphasizing the importance of cross-domain synergy and adaptive, intelligent building operation. These trends, synthesized in Figure 4, justify the development of a unified analytical framework (UEVIF) and a normalized metric (SPI) to systematically characterize and quantify synergy across integrated building systems.

4.3 Geographic and system patterns

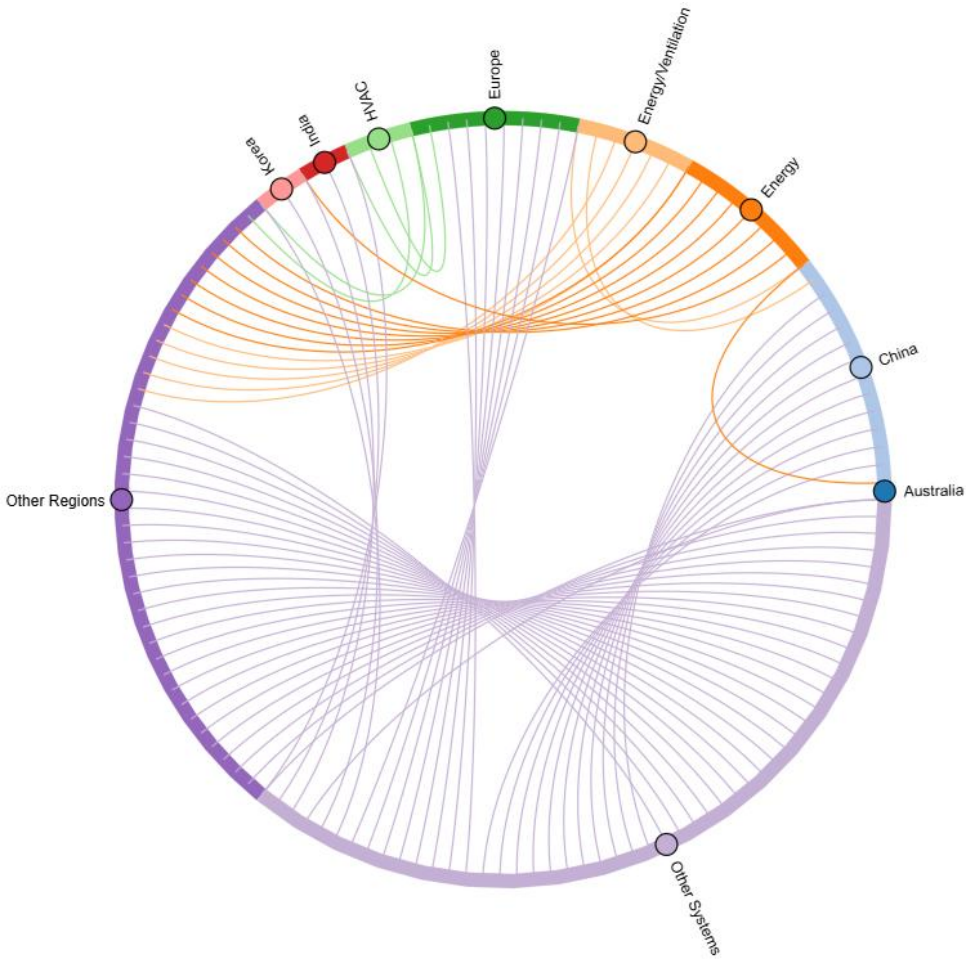

Figure 5. System–Location Relationships in Building Integration Studies. Chord diagram illustrating relationships between building system types and geographic regions in (E–W–V) integration research (2015–2025). Thickness of each connection represents number of studies linking specific systems (e.g., HVAC, energy, ventilation) to regional contexts.

The chord diagram in Figure 5 illustrates key geographical and systemic imbalances in contemporary E–W–V integration research. A dominant share of studies originates from China, where research has focused extensively on advanced HVAC optimization, smart building management systems (BMS), and low-carbon energy strategies. This reflects the country's rapid urbanization, climatic diversity, and strong policy emphasis on high-performance, energy-efficient infrastructure [40, 73, 84, 85, 86]. Europe is the second most active region, contributing significant research on adaptive comfort algorithms, district-scale retrofitting, and integrated passive–active system design, driven by stringent decarbonization targets and mature regulatory frameworks [36, 87, 88, 89, 90].

While less represented numerically, research from the United States and Australia contributes important case studies on mixed-mode building operations, passive system integration, and solar façade prototypes tailored to diverse climatic regions [45, 81, 91].

From a systems perspective, the predominance of the "Other Systems" category—which includes hybrid, cross-disciplinary, and multi-domain approaches—indicates a field gradually transitioning from siloed research to holistic, network-oriented integration frameworks. These approaches combine passive envelope strategies, advanced control systems, renewable energy coupling, and data-driven optimization. For instance, studies involving BIM-enabled LCA,

predictive load management, and multi-energy system (MES) planning highlight the increasing complexity and interdisciplinarity of integrated design [44, 54, 92].

However, the diagram also reveals a notable methodological limitation: nearly 70% of studies rely heavily on generic simulation environments rather than site-specific empirical data, raising questions about climatic transferability, real-world feasibility, and operational robustness of reported results. This over-reliance on simulation highlights the pressing need for standardized validation protocols, longitudinal case studies, and field-based datasets to strengthen the empirical foundations of E–W–V integration.

Geographically, vast regions—including Sub-Saharan Africa, Latin America, Southeast Asia, and the Middle East—remain underrepresented, despite facing acute challenges related to climate vulnerability, water scarcity, and resource constraints. Addressing these gaps will require integrating socio-economic and policy contexts, expanding empirical validation in diverse climates, and tailoring integration strategies to local building practices and infrastructure constraints. These regional disparities also emphasize the importance of developing transferable frameworks (such as UEVIF) that can adapt to varied climatic, economic, and policy environments.

.

4.4 Nature of system integration

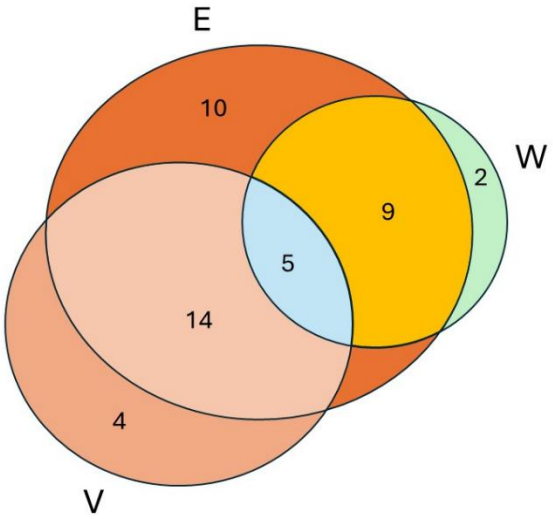

Figure 6. Distribution of 44 studies mapped according to their coverage of energy (E), water (W), and ventilation (V) systems.

Of the 107 studies included in the final dataset, a subset of 44 studies (Figure 6) was selected for detailed cross-domain mapping. These studies provided sufficient quantitative or system-level data to categorize interactions across the energy (E), water (W), and ventilation (V) domains.

Findings indicate that:

- 10 studies focused exclusively on energy
- 2 studies exclusively on water
- 4 studies exclusively on ventilation
- 14 studies integrated energy and water (E–W)
- 19 studies integrated energy and ventilation (E–V)

- 5 studies examined water–ventilation (W–V) interactions
- Only 5 studies investigated full three-domain synergy (E + W + V)

These results demonstrate that while dual-domain integration—particularly E–V systems—is relatively well explored, true tri-domain integration remains rare and significantly underdeveloped. This scarcity of full E–W–V studies confirm the necessity of a unified conceptual model capable of consolidating fragmented insights into a single analytical framework, as addressed through the development of UEVIF.

Beyond these quantitative patterns, the review identifies a deeper conceptual issue: many studies implicitly treat integration as additive rather than synergistic, examining combined technologies without fully addressing interdependencies, feedback loops, or systemic co-optimization. This limits the field's ability to develop robust, scalable integration frameworks. This additive framing prevents researchers from capturing emergent behaviours, interaction effects, and cross-domain performance gains that define true synergy, thereby reinforcing the need for a dedicated synergy metric such as the SPI.

To address the lack of historical coherence and conceptual maturity, Table 2 synthesizes the thematic evolution of E–W–V research into five developmental phases ranging from early passive strategies to fully integrated resource-nexus approaches. This structure highlights how research emphasis has progressively shifted toward digital intelligence, resource circularity, and systems thinking, reflecting broader transformations in building science and sustainability policy.

Recent studies have advanced understanding of E–W–V synergies by clarifying enabling technologies, operational strategies, and multi-system interactions. Notable insights include: (i) increasing adoption of digital-twin-enabled optimization, (ii) expansion of water–energy recovery loops in hybrid HVAC systems, (iii) growing emphasis on humidity- and IAQ-responsive control, and (iv) integration of renewable energy forecasting with water and ventilation scheduling.

Table 2. Summary of research evolution on E–V–W synergy in buildings, structured into five thematic sections. Each section reflects a distinct phase of research development, from passive design foundations to fully integrated resource nexus strategies, with representative studies drawn directly from literature.

Section	Theme / Era	Narrative Focus	Representative Studies (examples)
I. Passive & Mixed-Mode Foundations (2015 – 2017)	Early stage focusing on natural ventilation, adaptive comfort, and envelope optimisation as building-scale strategies to reduce operational energy demand.	Ventilation-driven savings, mixed-mode comfort, early NV control.	[93-95] [96, 97]
II. Integrated Simulation & LCA-	Tools like BIM, LCA, and	BIM-enabled LCA, dynamic load-split,	[44, 72, 74, 75, 77] [98]

Driven Design (2016 – 2021)	simulation platforms start integrating energy, ventilation, water and materials data for more holistic decision-making.	calibration of BES, envelope + HVAC integration.	
III. Digital Twins, Smart Control & Predictive Optimisation (2018 – 2023)	Transition to predictive models, grey-box MPC, and data-driven optimisation to couple systems dynamically and close simulation-to-operation gaps.	MPC, AI-based retrofit, predictive control, occupant disturbance modelling.	[39, 60, 62, 76, 99, 100]
IV. Multi-System Integration & Net-Zero Pathways (2022 – 2025)	Focus on system-of-systems synergy: PV + HVAC + storage, distributed MPC, multi-energy system (MES) planning, and policy-linked NZC roadmaps.	MES, NZC frameworks, BIPV, multi-domain flexibility, AI-enhanced RES integration.	[45, 50, 51] [80, 101] [102] [63]
V. Full E–V–W Nexus & Circular Resource Strategies (2022 – 2025)	Final stage where energy, ventilation, water and waste systems converge incorporating FEW nexus, recycled water, hot water forecasting, and urban agriculture synergies.	Building-integrated EWW, DHW forecasting, vertical farming, recycled WS.	[52, 55, 56, 81, 82] [34]

Note: This structure reflects chronological and conceptual evolution of E–V–W synergy research, highlighting key milestones and representative works from foundational studies to integrated, circular building ecosystem strategies. It also provides the empirical basis for positioning each technological and operational pathway within the Unified Energy–Water–Ventilation Integration Framework (UEVIF).

Recent research has greatly enhanced understanding of E–V–W synergies by clarifying a range of technological, operational, and systemic methodologies. Numerous studies on natural ventilation (NV), hybrid ventilation, and adaptive comfort strategies have demonstrated that passive and occupant-cantered control approaches can substantially reduce cooling energy demand by 15% to 75% [48, 93-95, 103]. These strategies also maintain acceptable thermal comfort levels across a wide range of climatic conditions. Such passive–active hybrids form the foundation of ventilation-driven synergy pathways captured within UEVIF.

Recent investigations have explored advanced envelope-integrated renewable technologies, including BIPV/T facades, DSF-PV hybrids, and semitransparent organic photovoltaic (ST-OPV) systems [46, 104-106]. These innovations illustrate how building envelopes can actively contribute to on-site energy generation and support broader decarbonization goals. Reported outcomes show energy production gains reaching up to 240 kWh m^{-2} yr^{-1}. These envelope-integrated systems represent key enablers of energy–ventilation and energy–water interactions by linking generation, thermal regulation, and airflow management within a single architectural layer.

At the operational level, an expanding body of research delves into smart control, predictive automation, and cost-effective sensing technologies. These studies illustrate how real-time feedback mechanisms can optimize indoor air quality (IAQ), thermal comfort, and energy consumption simultaneously [107-109]. This emerging domain of intelligent controls forms the backbone of tri-domain (E–W–V) synergy, enabling dynamic co-optimization and providing the performance data necessary for synergy quantification via the Synergy Performance Index (SPI).

Recent studies have expanded beyond individual buildings to introduce strategies for multi-system and urban-scale integration. These strategies encompass CHP–TES coupling, hybrid solar–gas Fresnel systems, and energy-sharing frameworks. Collectively, they represent a shift toward perceiving buildings as resource co-generative hubs functioning within broader circular city ecosystems [84, 110-112]. These urban-scale approaches signal a transition toward cross-scalar synergy, reinforcing the need for frameworks like UEVIF that can accommodate both building-level and district-level integration pathways.

These developments collectively demonstrate a shift from component-level enhancement toward multi-domain, cross-scalar resource coordination, providing strong justification for developing comprehensive, standardized synergy frameworks and metrics capable of evaluating both existing and emerging E–W–V integrations.

4.5 Technology-driven focus and underreporting of building typologies

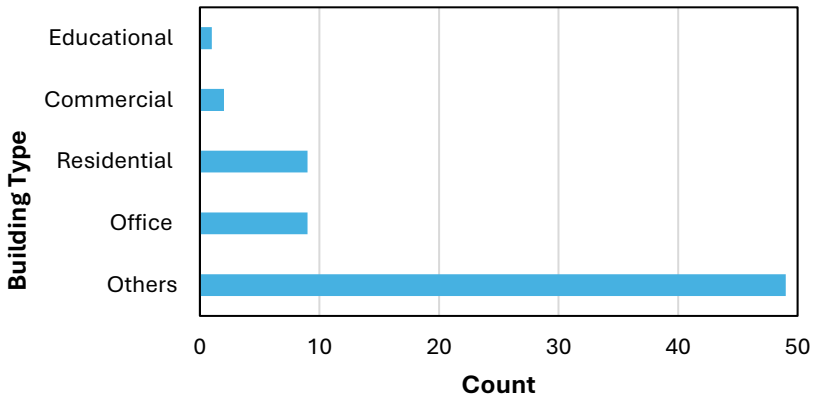

Figure 7. Distribution of building types represented in studies examining E–V–W integration, showing relative frequency of applications across different sectors.

The distribution of building typologies in Figure 7 reveals a pronounced imbalance in the existing research landscape. Nearly 77% of studies are categorized as "Other/Unspecified," indicating that a substantial portion of integration research does not explicitly identify the building type under investigation. This lack of typology definition reflects a methodological orientation toward system-level generalization rather than context-specific application.

This trend reflects a broader methodological orientation: approximately 78.7% of these studies prioritize system performance, control algorithms, or component-level optimization, often using generic simulation environments or prototype testbeds designed for cross-typology generalizability [41, 42, 45, 46, 81, 82, 87, 88, 90, 113, 114]. Such work is valuable for technological development but limits the ability to evaluate performance in real-world operational contexts. Consequently, many of these findings lack transferability to specific building archetypes where occupancy profiles, envelope characteristics, and operational schedules significantly alter integration outcomes.

Additionally, ~9.8% of unspecified studies examine multi-building or district-scale applications, where building type classification is inherently less relevant [84, 88, 90, 102, 113]. A smaller portion, ~5% explore foundational frameworks or conceptual models, focusing on transferable principles rather than specific building types [41, 45, 81, 105]. These conceptual studies play an important role in theory-building and often inform higher-level integration models such as UEVIF, though they do not provide performance validation across concrete typologies.

These trends indicate that the field remains heavily technology-centric, prioritizing advanced controls, sensor integration, and hybrid technology systems over building-specific implementation. While this focus has accelerated innovation, it highlights a major research gap: empirical validation across diverse building typologies such as hospitals, schools, laboratories, industrial facilities, and high-density residential towers. Without such typology-aware evidence, it remains difficult to assess how integration strategies scale, how synergistic effects vary across contexts, or how SPI values would differ for buildings with distinct functional requirements and operational constraints.

Future work should integrate real-world performance assessments, facility-specific operational constraints, and context-aware design strategies to ensure that system integration methodologies can be effectively transferred from simulation to practice. Developing typology-specific datasets and multi-building calibration protocols is therefore essential to advance UEVIF's applicability and enable robust benchmarking of SPI outcomes.

4.5 Key Gaps and future Research Needs

A detailed synthesis of the reviewed literature reveals a number of persistent limitations that continue to shape the landscape of integrated energy–water–ventilation (E–W–V) research. Although the past decade has seen rapid advancements in modelling, simulation, and digital system design, the field still faces substantial obstacles that hinder its transition from theoretical innovation to widespread real-world implementation. These gaps span empirical validation, modelling fidelity, systems integration, socio-technical constraints, scalability, emerging technologies, and the role of data-driven intelligence in building operations.

A dominant issue across the literature is the heavy reliance on simulation-based assessments with limited real-world verification. While simulations consistently report considerable

improvements in energy efficiency, indoor air quality, or water reuse, very few studies validate these outcomes using measured, post-occupancy performance data. As a result, a significant "simulation-to-practice" gap persists. This gap is compounded by inconsistent baseline assumptions and the absence of standardized measurement and verification frameworks, which makes the comparison of results across studies difficult and undermines confidence in reported performance gains. Without multi-climate, multi-building empirical verification, it remains challenging to determine how integrated systems perform under real operational conditions—where occupancy patterns, maintenance practices, climate variability, and behavioral factors significantly influence outcomes.

Addressing this gap is crucial for SPI development, since synergy quantification relies on accurate baseline-to-integrated performance comparisons that simulations alone cannot robustly provide.

Parallel to this, there are important limitations in modelling and digital twin (DT) calibration practices. Although BIM and DT technologies have gained widespread attention, many studies remain conceptual and do not extend to operational validation or reproducibility. Calibration methods vary widely, and the lack of shared, open-access calibration datasets prevents transparent cross-study benchmarking. Moreover, DT workflows often omit critical variables such as indoor air quality measurements, dynamic water-use profiles, and occupant-driven variability, all of which are essential for achieving accurate and transferable digital representations of building performance. A more integrated DT–BIM pipeline, supported by standardized ontologies and interoperable data structures, is necessary to link design-time simulations with operation-time data in a meaningful and reproducible manner.

Such improvements are essential for enabling real-time synergy optimization, automated SPI calculation, and adaptive control visualizations within operational building platforms.

Another major gap lies in the limited extent to which true synergy is addressed. Most studies continue to examine only dual-domain interactions—typically energy–ventilation or energy–water—while full three-domain integration (E + W + V) remains rare. This narrow scope leads to fragmented optimization, redundant system sizing, and an inability to capture cross-domain trade-offs and feedback dynamics. Important linkages, such as the interaction between humidity control and domestic hot water use, remain underexplored. Addressing this requires a shift from additive combinations of technologies toward synergy-aware control frameworks, supported by integrated datasets and unified performance indicators that measure energy, water, and indoor environmental quality concurrently.

The development of SPI directly responds to this gap by providing a normalized metric that can quantify cross-domain interaction strength rather than just aggregated performance.

These technical limitations are compounded by broader socio-technical and policy challenges. Although global climate policies increasingly promote cross-sectoral efficiency, their translation into building-level operational frameworks remains limited. Many studies focus on technology-centric approaches without adequately addressing occupant behavior, organizational processes, market constraints, or regulatory barriers. The result is a disconnect between policy aspirations and operational feasibility. For integrated systems to be broadly adopted, policies must be supported by clear performance-to-policy translation frameworks

that connect system operation, adaptive controls, indoor environmental standards, and water-efficiency measures into actionable guidelines for design and retrofit processes.

Bridging this gap will require mapping UEVIF outcomes to policy levers and developing SPI thresholds that correspond to regulatory performance benchmarks.

Scalability and replicability represent further obstacles. Many studies demonstrate promising results at the prototype or simulation level, yet these findings seldom translate into diverse building typologies or climates. As a result, integrated E–W–V systems are often validated only in highly controlled environments or within a single building category. This limits the ability to transfer knowledge to more complex or underserved settings such as hospitals, industrial facilities, educational campuses, or high-density residential buildings. Future efforts must therefore focus on multi-site comparative trials, district-scale deployments, and modular integration frameworks that enable systems to be adapted and replicated across varied operational contexts.

Such real-world diversity is necessary to test the robustness of synergy pathways within UEVIF and evaluate how SPI varies across climate zones and functional typologies.

In addition to these mainstream gaps, the literature also highlights a series of emerging opportunities that remain largely underexplored. Frontier technologies such as Direct Air Capture integrated with HVAC systems, solar exoskeletons, hybrid photovoltaic–thermal ventilation systems, and building-integrated urban agriculture show substantial promise but lack empirical validation. Most evaluations of these technologies remain conceptual or simulation-based, leaving unanswered questions regarding maintenance, reliability, life-cycle performance, and user acceptance. Full-scale prototypes supported by rigorous measurement and verification are essential to determine whether these innovations can become practical components of future building ecosystems.

These emerging synergies offer new pathways for expanding UEVIF and extending SPI into next-generation building system evaluation.

Finally, the rapid rise of AI, machine learning, and predictive control introduces both opportunities and challenges. While forecasting models are growing more sophisticated, many remain highly site-specific and lack cross-region generalizability or uncertainty quantification. More critically, AI forecasts often do not translate into closed-loop control architectures, leaving a gap between algorithmic performance and real-world energy or water savings. Progress in this domain requires the development of multi-climate training datasets, open-source benchmarking platforms, and seamless AI-to-MPC (Model Predictive Control) pipelines that ensure data-driven intelligence contributes to measurable improvements in building operation.

Integrating AI with synergy-aware control logic represents a critical frontier for enabling real-time SPI enhancement and operationalizing E–W–V synergy in practice.

Overall, the key gaps identified across the literature reveal the need for a new generation of integrated building research that is empirically rigorous, multi-domain, digitally enabled, socio-technically informed, and scalable across diverse contexts. Addressing these limitations is essential for moving integrated E–W–V systems from isolated technological demonstrations to widespread deployment as foundational components of climate-resilient, net-zero-ready building environments.

These insights provide the conceptual and empirical justification for the UEVIF framework and the Synergy Performance Index, enabling integrated evaluation of buildings as interconnected resource systems rather than isolated subsystems.

Table 3. Expanded thematic classification of research gaps and future Directions for integrated E–W–V Systems (2010–2025).

Category	Gap Theme	Current Limitation / Challenge	Future Research Direction	Representative Studies
1. Evidence and Validation Gaps	From simulation to metered performance	Numerous studies concerning the integration of E–W–V predominantly depend on simulations, lacking empirical verification through metering that connects optimized control to actual outcomes in energy consumption, CO_2 levels, or indoor air quality (IAQ).	Establish multi-site M&V frameworks linking real-time control data to post-occupancy metrics across diverse climates and building types.	[40] [41] [36] [35] [115] [37, 87] [76] [42, 45, 51] [80] [90, 114, 116, 117] [46, 93, 94] [118] [95, 119] [98] [84, 96, 103, 109] [47, 111] [48]
	Baseline & verification consistency	The lack of consistent baseline assumptions and the use of non-standard Measurement and Verification (M&V) models diminish the comparability of reported performance outcomes.	Adopt IPMVP-aligned verification protocols, integrating occupancy, weather, and system interactions for consistent synergy evaluation.	[36, 44, 71, 77, 78] [38, 50, 72] [42] [39, 120] [31] [34, 63, 121, 122] [58, 91, 105, 123] [106, 112, 124-126] [59]
2. Modelling and Digital Twin Calibration	BIM–DT integration and data fidelity	Digital twin (DT) and Building Information Modeling (BIM) frameworks frequently lack calibration, emphasizing	Develop DT–BIM integration pipelines with open calibration datasets linking simulation and operation data	[44, 49, 74, 75, 79] [87-89, 113] [43, 127-129] [57, 82, 102, 104, 130] [53, 60, 85, 86, 99, 131, 132]

		conceptual design over the assessment of measured indoor air quality (IAQ) and operational performance. .	streams for reproducibility.	[61, 100, 133] [92] [134]
	Calibration reproducibility and transparency	The cross-validation between simulation and field data is currently constrained, with a limited number of shared calibration datasets or publicly available benchmarks.	Establish global repositories for calibration datasets linking IAQ, thermal comfort, and HVAC system efficiency across climates.	[42, 45, 71, 76, 77, 87] [80, 90, 116, 121] [34, 94, 95, 114, 117] [48, 61, 62, 83, 86, 92, 96, 98, 100, 109, 111, 119, 123, 126, 132] [54]
3. Integration of Energy–Water–Ventilation Systems	Synergy-aware frameworks	The subsystems of energy, water, and value (E–W–V) are infrequently optimized in conjunction, leading to resource redundancies and untapped potential for synergies.	Develop synergy-aware MPC frameworks integrating real-time data across water reuse, HVAC, and IAQ systems for holistic control.	[35, 38, 39, 49, 50, 71, 113] [31, 43, 55, 57, 90, 121, 127-129] [34, 46, 63, 82, 94, 102, 114, 117, 118, 122, 130]55] [105]
	Cross-domain datasets and metrics	The absence of standardized metrics that encompass the integrated performance of E–W–V hinders both comparability and the validation of models.	Design integrated indicators combining EUI, WUI, and IAQ indices for system-level benchmarking and lifecycle reporting.	[31, 51, 71, 72, 74, 89, 115, 120]36, 37][116, 121] [34, 46, 82, 95, 102, 122, 130] [47, 59, 91, 96, 103, 112, 119, 125]

4. Socio-Technical and Policy Barriers	Policy–performance linkage	National net-zero carbon policies have yet to be effectively translated into actionable strategies for building-level control or retrofitting.	Align NZC frameworks with adaptive, occupant-centred control protocols and region-specific benchmarks for E–W–V integration.	[42, 45, 50, 51, 55, 76, 79, 80, 113, 127] [31, 34, 46, 52, 57, 58, 63, 82, 91, 93-96, 98, 102, 104, 105, 107, 114, 116-119, 122, 123, 130, 135]
	Replicability and scalability barriers	Most E–W–V frameworks are constrained by their site-specific nature or are limited to individual case studies, which impedes their scalability.	Develop multi-building and district-scale frameworks validated under varied operational and climatic conditions.	[35-37, 41, 75, 77, 79, 87, 89, 113, 136] [38, 39, 43, 52, 57, 63, 90, 116, 121, 122, 135] [93, 94, 98, 104, 118, 119, 123] [48, 84, 96, 106, 111, 112, 125, 126]
5. Frontier Technologies and Emerging Directions	Carbon and life-cycle integration	Life Cycle Assessment (LCA) boundaries frequently omit considerations of ventilation and water reuse metrics, thereby constraining comprehensive carbon accounting.	Embed ventilation rate, water circularity, and comfort metrics in $LCCO_2$ assessments for integrated sustainability evaluation.	[71, 72, 75] [38, 50, 76, 89] [39, 43, 90, 120, 127] [31, 57, 129] [46, 82, 114, 117, 130] [34, 102, 104] [98, 105, 107, 119] [47, 103, 124] [48, 53, 85] [60, 131] [100, 101]
	Emerging technologies and hybrid systems	Technologies such as Direct Air Capture (DAC), solar exoskeletons, and hybrid photovoltaic–thermal ventilation systems have yet	Pilot full-scale integrated systems and publish M&V-based performance of hybrid E–W–V prototypes under field conditions.	[38] [42, 45, 46, 114, 117, 122] [46] [104, 105, 123] [34, 93, 94] [95, 118] [48, 84, 111, 126]

		to be validated in practical settings.		[53, 85, 86, 132] [60, 99, 101] [61] [92, 133] [62, 134] [83] [54, 64, 137]
6. Cross-cutting AI, Data, and Forecasting Challenges	Forecast-to-control gap	Machine learning and forecasting models frequently do not extend to the implementation of closed-loop control or undergo comprehensive validation. ss	Integrate AI-driven forecasts with MPC algorithms and open datasets to bridge predictive and operational control layers.	[34, 39, 43, 52, 58, 80, 98, 102, 105, 107, 114, 117, 135] [59, 84, 96, 103, 109, 111, 125, 126] [53, 60, 61, 86, 100, 101, 132, 133] [54, 62, 64, 83, 92, 134, 137]

Note: This expanded table integrates all studies (shown in Table A1 in appendix) from the uploaded dataset, categorized across six thematic domains. It maintains comprehensive coverage without omission or duplication, aligning with the synthesis framework of the main review paper.

5. Limitations

Despite notable advancements in integrated building system research, several enduring limitations continue to constrain the field's maturity, scalability, and real-world applicability. One of the most prominent limitations is the persistent reliance on simulation-based methodologies, which often dominate the evidence base. While simulations provide valuable insights into potential performance gains—such as reductions in energy use, carbon emissions, or improvements in indoor air quality—they frequently operate under idealized assumptions that do not reflect the complexities of day-to-day building operations. Factors such as occupant behavior, maintenance practices, equipment aging, and climatic variability are difficult to model accurately, yet they significantly influence actual system performance. As a result, many reported improvements remain unverified in real-world settings, producing a substantial discrepancy between theoretical potential and operational reality.

This discrepancy also restricts the applicability of synergy-based evaluation tools such as the SPI, which require validated baseline and operational datasets to derive reliable synergy scores.

A related limitation is the marked lack of large-scale, long-duration empirical validation. Only a small proportion of studies incorporate monitored, post-occupancy data, and even fewer evaluate integrated systems across multiple building types or climatic regions. The absence of such validation makes it difficult to determine whether integrated E–W–V configurations perform consistently across different operational contexts. Without such evidence, technology readiness levels remain low, and the scalability of integrated solutions remains uncertain. This challenge is further compounded by inconsistent assumptions in baseline modelling and the

absence of universally accepted measurement and verification protocols, which restrict cross-study comparability and weaken the foundations for meta-analytic synthesis.

Consequently, many existing studies cannot be mapped into standardized UEVIF categories with high confidence, limiting the generalizability of synergy pathways.

Limitations also arise from significant geographical and typological imbalances present in current research. A majority of studies originate from a small number of technologically advanced regions, particularly China, Western Europe, and North America. Meanwhile, climate-vulnerable and resource-constrained regions—such as Sub-Saharan Africa, Latin America, South Asia, and the Middle East—are underrepresented, despite the fact that integrated E–W–V solutions could offer substantial benefits in these areas. This geographical skew restricts understanding of how integrated systems might perform in diverse contexts, including regions with unreliable energy supply, high water stress, informal construction practices, or limited access to advanced technology. Similarly, research is predominantly focused on residential and office buildings, while other critical typologies—such as hospitals, laboratories, schools, and industrial facilities—remain significantly underexplored, even though these settings often present complex operational demands where integration could be particularly impactful.

The limited representation of these building types also restricts the development of typology-specific SPI benchmarks and hinders accurate cross-context comparison.

Another limitation involves the conceptual fragmentation and methodological inconsistencies that persist across the literature. Definitions of key concepts—such as "net-zero carbon buildings," "synergy," or even "integration"—often vary, leading to conceptual ambiguity and inconsistent boundaries in system modelling. This variability complicates cross-study comparison and hinders the establishment of standardized frameworks for integrated building analysis. Additionally, many studies employ generic simulation environments designed for broad applicability rather than real building-specific modelling. While this enhances generalizability, it can obscure the influence of contextual variables such as climate dynamics, occupant habits, and socio-technical conditions.

This inconsistency underscores the necessity of UEVIF, which provides standardized integration categories and synergy pathways to unify disparate conceptual approaches.

Finally, the field continues to face challenges related to digital integration and data interoperability. Building Information Modelling (BIM), Digital Twins (DTs), and IoT-based sensing platforms offer the potential to link design, operation, and performance evaluation within unified workflows. However, many existing studies remain conceptual and do not progress toward fully calibrated, operationally aligned DT implementations. The lack of shared datasets, interoperable data schemas, and transparent calibration protocols limits the ability to reproduce results and build upon prior research. Furthermore, integrating water systems and ventilation metrics into lifecycle assessment tools remains difficult, limiting the capacity to evaluate the full environmental implications of integrated E–W–V designs.

Advancement in this domain is essential for enabling automated SPI calculation, real-time synergy tracking, and full deployment of UEVIF in operational buildings.

In summary, the limitations identified in this review demonstrate that while the field of integrated E–W–V building systems has grown considerably, substantial challenges remain.

These challenges highlight the need for robust empirical evidence, broader geographic and typological representation, standardized methodological frameworks, and deeper socio-technical integration. Addressing these limitations will be essential for advancing integrated systems from conceptual promise to operational reality and supporting the development of climate-resilient, resource-efficient buildings at scale.

These limitations also justify the introduction of UEVIF and SPI as tools designed to overcome conceptual fragmentation and enable consistent, cross-domain performance evaluation.

6. Future research directions

To advance the integration of Energy–Water–Ventilation (E–W–V) systems beyond their current technical and conceptual limitations, future research should transition from descriptive and simulation-based studies toward empirically validated, standardized, and predictive frameworks that can support real-world deployment. The foremost priority lies in developing large-scale, long-duration demonstration projects that directly link simulation outputs with monitored field performance. Long-term empirical datasets capturing variations in energy demand, water reuse dynamics, ventilation efficiency, and indoor air quality across diverse climatic and occupancy profiles are essential for increasing the reliability, comparability, and transferability of existing models. Establishing open-access repositories containing high-resolution operational data would significantly enhance transparency, reproducibility, and the capacity for meta-analytical benchmarking of integrated systems [138].

Such datasets would also serve as the foundation for calibrating and validating SPI across diverse building types, climates, and operational conditions.

Equally important is the methodological standardization of performance evaluation. At present, inconsistent definitions of integration boundaries, synergy efficiency, and baseline establishment impede meaningful comparison between studies. Future work should adopt internationally recognized frameworks—such as the International Performance Measurement and Verification Protocol (IPMVP)—to ensure consistency in performance monitoring, reporting, and validation. The introduction of a unified benchmarking metric, such as the proposed Synergy Performance Index (SPI), would allow for systematic cross-domain assessment of E–W–V efficiency. Embedding uncertainty and sensitivity analyses within such standardized protocols would further strengthen the robustness of predictive modelling and help stakeholders evaluate operational risks, interdependencies, and trade-offs [139].

Incorporating SPI into verification protocols can create a universal synergy metric analogous to EUI or IAQ indices, advancing performance comparability across regions and building types.

Expanding the scope of research beyond dual-domain interactions represents another pressing future direction. The majority of existing studies continue to emphasize energy–ventilation or energy–water interactions, while water–ventilation synergies remain critically underexamined despite their central role in shaping humidity loads, water-heating demand, and indoor environmental quality. Future research should therefore extend the E–W–V framework toward a broader resource-nexus perspective that incorporates waste streams, material flows, and food–energy–water interlinkages at building, district, and urban scales. Such an approach

aligns with circular economy principles and urban metabolism theory, ensuring that integrated building systems contribute to city-wide resource resilience and climate adaptation strategies. Furthermore, there is a need to investigate underrepresented building typologies—including healthcare, industrial, and educational facilities—whose distinctive operational profiles necessitate more customized integration strategies [140].

This expanded scope will also allow UEVIF to evolve into a multi-scalar nexus framework and support district-scale SPI assessment.

Beyond the technical domain, the socio-technical dimension of E–W–V integration requires far greater scholarly attention. The successful deployment of integrated systems depends not only on engineering innovation but also on user engagement, social acceptance, facility management practices, and organizational readiness. Future studies should therefore incorporate behavioural modelling, participatory design methods, and human-in-the-loop control mechanisms to better understand how occupant interaction influences performance outcomes. Research that couples adaptive occupant behaviour with intelligent, learning-based control algorithms offers significant potential to optimize comfort, reduce resource consumption, and increase user acceptance of integrated systems [141].

Embedding these behavioural modules within UEVIF and linking them to SPI scoring can support more realistic evaluations of synergy under variable human-driven conditions.

Finally, bridging the gap between research innovation and widespread adoption requires a more supportive policy, regulatory, and financial landscape. High upfront costs, fragmented supply chains, and the absence of shared performance contracting mechanisms currently limit the scalability of integrated retrofits, particularly in small enterprises and public-sector buildings. Future investigations should therefore explore innovative policy instruments, incentive schemes, and financing models that link system performance to verifiable environmental and social benefits. Embedding the proposed Unified E–W–V Integration Framework (UEVIF) within national building codes, retrofit standards, and decarbonization roadmaps would accelerate mainstream adoption and support the broader transition toward net-zero carbon and circular resource economies [142].

Policy integration of SPI—similar to how LEED or BREEAM incorporate energy metrics—could institutionalize synergy evaluation as a requirement for future building projects.

7. Conclusion

This review has demonstrated that the integrated management of energy, water, and ventilation (E–W–V) systems constitutes a critical pathway for advancing sustainable development in the built environment. In the context of escalating climate risks, resource scarcity, and urbanization pressures, coordinated E–W–V integration offers a systems-based approach to reducing environmental impacts while simultaneously enhancing resource efficiency, indoor environmental quality, and operational resilience. The synthesis of the reviewed literature confirms that integrated E–W–V strategies can deliver substantial performance gains, including energy-use reductions of 30–70%, water-consumption savings of 20–40%, and measurable improvements in indoor air quality when supported by coherent design and operational strategies.

Despite these demonstrated benefits, the review reveals that progress toward fully integrated E–W–V systems remain constrained by fragmented research practices, inconsistent modelling assumptions, and a continued reliance on simulation-based assessments with limited empirical validation. Most existing studies prioritize dual-domain interactions—typically energy–ventilation or energy–water—while comprehensive tri-domain integration remains rare. This fragmentation limits the ability of current approaches to capture cross-domain feedbacks, evaluate systemic trade-offs, and support robust, transferable solutions aligned with sustainable development objectives.

In response to these challenges, this study introduces the Unified Energy–Water–Ventilation Integration Framework (UEVIF) and the Synergy Performance Index (SPI) as complementary methodological contributions designed to support holistic assessment and decision-making. The UEVIF provides a structured lens for conceptualizing integrated building systems within their broader socio-technical and environmental contexts, while the SPI offers a normalized metric for evaluating synergy effects across energy, water, and indoor environmental performance. Together, these tools establish a foundation for more consistent benchmarking, comparative analysis, and policy-relevant evaluation of integrated building systems.

From a sustainable development perspective, the proposed framework and metric have direct implications for research, practice, and governance. By enabling more transparent evaluation of integrated system performance, they can inform evidence-based building codes, retrofit strategies, and sustainability assessment frameworks aligned with international climate and development agendas, including the United Nations Sustainable Development Goals. Moreover, embedding E–W–V integration within circular resource-flow thinking positions buildings as active contributors to urban sustainability transitions rather than passive consumers of resources.

Looking forward, advancing integrated E–W–V systems will require a decisive shift toward long-term empirical validation, multi-climate comparative studies, and the integration of behavioral, organizational, and policy dimensions into system design and operation. Strengthening links between digital-twin technologies, adaptive control strategies, and real-world performance monitoring will be essential for translating conceptual innovation into scalable, practice-ready solutions. By aligning technological integration with sustainable development principles, future research and implementation efforts can accelerate the transition toward climate-resilient, resource-efficient, and socially responsive built environments.

Appendix

Table A1. Key gaps in existing literature on E/W/V integration research. Table synthesizes critical shortcomings identified across current studies including limitations in metered validation, scenario input quality, policy–performance alignment, and simulation translation and outlines targeted future research directions needed to enhance methodological robustness, contextual accuracy, and real-world applicability of building system integration research.

Research Gap Identified	Current Limitations / Evidence	Recommended Future Research Priorities	Key Sources
From optimized control → metered savings	Many BMS studies report simulation gains; fewer show meter-verified kWh & CO_2	RCTs / M&V linking optimized control to measured energy/CO_2 across climates	[40]
Scenario models need better building-type inputs	LEAP studies' credibility hinges on precise activity parameters (stocks, device uptake)	High-resolution EUI/device profiles by building type to tighten SD-LEAP inputs	[78]
Policy–performance bridges	nZCB definitions are maturing, but operational pathways for HVAC energy vary by climate	Map definition → controls/ventilation setpoints and publish climate-zoned guidance	[79]
From simulation to metered savings (TABS)	Most results are simulation/heuristic validation; limited M&V for real buildings	Publish meter-verified kWh/comfort outcomes for OLSA-guided TABS across climates.	[41]
High-rise PV evidence base	Most studies focus on small-scale residential; fewer medium-/high-rise office cases.	Expand office-building PV peak-shaving studies with measured (metered) CO_2 impacts.	[79, 136]
Hybrid-TABS design methodology	Prior to OLSA, no appropriate design methodology widely available.	Validate OLSA-like methods across climates/uses; publish open tools.	[41]
Simulation → metered outcomes	BIM/FirstRate5 & PV studies report simulation indices and daily CO_2 totals.	Conduct M&V studies translating optimisation/sensitivity to kWh and kg-CO_2 savings.	[44]
Baseline & verification methods across sites	Savings depend on robust baselines; transfer-function models used, but cross-site comparability varies	Standardize IPMVP-aligned baselining and long-term M&V across climates	[36]
Seasonal comfort management in mixed-mode	Small summer comfort shift under ACA while saving energy	Couple ACA with ventilation/air-speed strategies to stabilize summer comfort	[36]

Seasonal effectiveness of DCV	Prior work notes DCV-based ventilation reduction is most effective in very hot/cold seasons; in mild seasons, more ventilation can even save energy	Multi-season M&V campaigns quantifying DCV benefits and IAQ response across climates; publish control logic and datasets.	[35]
From simulation to meters for BMS optimisation	2024 BMS study is simulation-centric (even if data-informed)	Controlled trials reporting metered kWh and comfort/IAQ impacts of optimisation vs. baseline in real offices.	[40]
Replicable ACA implementations	Adaptive algorithms work, but implementations vary	Open protocols for ACA tuning, comfort feedback loops, and failure-mode handling; multi-site replications.	[36]
Lifecycle data integration for E/W/V	Lack of open, interoperable data-integration linking design ↔ operation (HVAC/ventilation/water)	Publish IFC/ontology extensions + DT pipelines focused on operational variables; release reference implementations	[74]
Meter-verified outcomes for DT/BIM-guided ops	Frameworks dominate; few studies report metered kWh/IEQ after changes	Run multi-site M&V reporting hourly energy & CO_2 + comfort/IAQ before/after DT/BIM interventions	[74]
BIPV evidence in non-low-rise offices	BIPV literature skews to frameworks/ratings; limited monitored office/high-rise cases	Expand monitored BIPV studies reporting peak reduction & daily CO_2 with strategy detail	[49]
Calibration reproducibility & NV links	Reviews note reproducibility issues and need to connect calibrated models to NV/IEQ analyses	Standardised datasets & protocols (CVRMSE/NMBE) tied to NV/IEQ outcomes	[77]
Operation-stage modelling of water use	Operation stage mentions water, but quant methods and validation are thin	Develop calibrated water-use sub models and link to E/W/V trade-offs within BIM-LCA	[71]
Unified $LCCO_2$ assessment usable in design	Methods exist but no single, unified framework widely adopted in practice	Standardise a design-stage $LCCO_2$ workflow with agreed boundaries and databases	[75]
Metered validation for urban energy maps	City-scale models validated ($R^2 \approx 0.76$) but limited meter-level follow-through	Publish datasets linking hourly CDH ↔ kWh at building level across urban/rural	[115]

Meter-verified outcomes for DT-supported TABS	Methodology papers rarely report metered kWh/CO_2 and comfort after deployment	Run multi-site M&V of TABS with DT-derived control; publish datasets and open control logic	[87]
Operational energy + ventilation metrics in LCA tools	LCA estimators emphasise energy/CO_2 breakdowns but rarely integrate ventilation/IEQ metrics	Co-report ACH/L·s-person, indoor CO_2 alongside kWh and kg-CO_2 in residential/commercial cases	[72]
Field M&V for MOF-based ventilation	Predominantly simulation-based results; few metered buildings	Pilot and publish multi-site M&V (kWh, IAQ, comfort) for MOF-based ARS	[37]
From UBEM to building playbooks	Regional models highlight variability; practitioners need building-level guidance	Translate UBEM outputs into per-measure guidance incl. ventilation/IAQ co-benefits	[89]
HRBs: robust NV with safety/comfort	NV potential must be balanced with smoke and comfort constraints	Control-ready NV strategies for HRBs with multi-objective criteria	[113]
District KPIs to include ventilation	Energy/CO2 KPIs strong; IAQ/vent metrics often missing	Add IAQ/CO2/ACH to dashboards alongside energy/CO2 KPIs	[88]
Indoor-ready DAC modules are not yet commercially available	Promising IAQ + energy benefits remain theoretical without deployable modules.	Prototype & pilot HVAC/DAC units in public/commercial buildings; measure IAQ, energy, maintenance realities.	[38]
Limited meter-verified impacts for MPC-ready grey-box models	Most results focus on modelling accuracy rather than long-term building energy/carbon outcomes.	Longitudinal M&V of kWh and CO_2 with MPC vs conventional control across climates and building types.	[76]
NZC case studies rely on simulations; few high-rise/offices metered validations	Bridging simulation–operations gap is essential to generalise NZC pathways.	Publish post-occupancy data: heat pump COPs, PV/wind yields, demand response and BESS performance.	[51]
Unified, reproducible carbon-calculation workflows	Different boundaries and methods hamper comparability across NZC cases.	Adopt open, standardised LCA/LCCO_2 frameworks aligned with system-boundary guidance; release datasets.	[50]
From prototypes to M&V: solar exoskeletons	Integrated structure-shading shows strong simulated	Field pilots with metered energy/comfort +	[45]

	gains; few metered buildings	embodied tracking across climates	
RFH/TABS: energy outcomes over seasons	Control results report comfort RMSE; seasonal kWh/CO_2 often missing	Longitudinal M&V comparing distributed-MPC vs rule-based across climates	[42]
Occupant-aware ID → closed-loop savings	SPDI validated on ID metrics; need building-level energy/peak reductions	Deploy SPDI-enabled control in offices; report kWh, peak, comfort vs baseline	[39]
Planning → operations for IES + V2G	Stochastic plans show potential; operations uncertainty & user behaviour critical	Implement pilots with EV/V2G participation and quantify realised CO_2/cost	[80]
Climate/operations-normalised M&V for controls & glazing	Headline % savings vary with climate, operations, and baseline	Publish metered multi-site M&V with weather/occupancy normalisation for HVAC controls & glazing retrofits	[43]
Replicable VE playbooks with measured outcomes	Strong simulation/case evidence; need replicable packages across typologies/climates	Develop regional VE+EEM playbooks and report post-occupancy kWh/comfort persistence	[127]
WS under-reported in E/W/V frameworks	Water services interact with energy/ventilation but are often siloed	Integrate pump VSDs, pressure control, and hot-water recirculation efficiency into whole-building reporting	[128]
Boundary alignment in carbon assessments	Systemic boundary choices change conclusions; hampers comparability	Adopt transparent, systemic boundaries & hybrid LCA for E/W/V interventions; report both embodied and operational	[120]
Operational M&V for 5GDHC at building/district scale	Most results are conceptual or planning-level; limited measured performance	Deploy pilots reporting loop temps, COPs, kWh/kW, heat-sharing effectiveness across seasons	[90]
DHW optimisation with health safeguards	Energy-saving measures trade off with Legionella risk and user behaviour	Multi-disciplinary trials combining energy metering with microbiological monitoring and occupant demand models	[55]
Standardised frameworks for building-integrated E-W-Waste	Heterogeneous solutions hinder scaling and comparability	Develop open protocols and economic models for decentralised E/W/W services	[31]

Open DHW datasets & reproducible pipelines	Forecasting results are dataset-specific; limited open benchmarks	Release anonymised multi-site DHW datasets; standardise RMSE/MAE protocols for MPC use	[52, 135]
Semantic interoperability in practice	Many deployments remain siloed; hard to scale DSM	Publish open ontologies/APIs; demonstrate cross-vendor, cross-domain apps with measured benefits	[121]
Embedding systemic water solutions in building projects	Ecosystem-service approaches underused in buildings	Pilot ICWs/SuDS integrated with building water/energy monitoring; report multi-benefit KPIs	[129]
Operational analytics for passive survivability	Rising heat risk; need rapid diagnostics and public code	Deploy SBOI/ACH analytics at scale; publish code/data and measured outcomes	[116]
Behavior-aware DHW programs	Large EWH savings hinge on habits and product stock	Labelling/incentives for efficient heaters; set-temp nudges; smart-control trials	[57]
Safe adoption of recycled water in buildings	QA/regulation/dual-piping barriers; CECs raise risk concerns	Pilot dual-piping with robust QA/QC; coordinate with public health; monitor CECs	[82, 130]
From synergistic DR simulation to metered outcomes	Strong sim results; few building-level M&V reports	Pilot synergistic DR (electric+heat) with metered kWh/comfort/IAQ and RES-curtailment metrics	[114, 117]
Interconnection strategies at precinct/building scale	Urban interconnection shows large system benefits	Downscale to campus/precinct micro-grids with clear resiliency & cost KPIs	[122]
PV-window durability & visual/thermal comfort in use	Prototype metrics promising; in-situ performance unknown	Long-term pilots reporting U/SHGC/AVT drift, glare, occupant comfort, and HVAC impacts	[46]
Daylight–electric coordination in real retrofits	Reviews report coordination gaps despite tech availability	Open datasets + reference control sequences (BIM-IoT) and post-occupancy metering	[63]
Forecast-to-control bridge for IES	Better forecasts must translate to dispatch/DR savings	MPC using synergy-aware forecasts; publish savings vs baselines	[102]
Urban agriculture–building thermal integration playbooks	Large GHG cuts possible but case-specific	Templates for HX sizing, control & resilience; LCA + M&V bundles	[34]
Lack of standards for MMV operation/control	Window schedules and mode switching drive	Develop standardized MMV control protocols;	[93]

	savings but are inconsistently applied	validate with monitored buildings	
Limited coupling of CFD/BES/experiments across design stages	Method choice impacts accuracy, cost, and adoption in multi-storey NV	Adopt proposed process model; build benchmark datasets for validation	[94]
Real-world validation of NV + diffuse inlet + TABS	Simulated benefits need field proof and commissioning guidance	Pilot deployments in diverse climates; draught-free NV design guides	[118]
Operational longevity of NVS in schools	Maintenance and operational practices affect IAQ and savings	Long-term monitored studies; teacher training; IAQ alarms (CO_2)	[95]
Under-developed environmental models for BIST	Most studies focus on energetic/thermal; environmental impacts overlooked	Develop thermal/optical/environmental co-models; explore PCM, nanofluids, concentrating collectors	[104]
Controller design for integrated NV+HVAC	Potential energy savings depend on accurate comfort prediction (PMV)	Extend MGFC to different climates and occupancy patterns; compare to MPC	[123]
BIPV/T geometry & control optimization	Slight cooling penalty needs mitigation while maximizing PV cooling	Optimize cavity geometry, transparency ratio, and seasonal control strategies	[105]
MM office comfort	Few longitudinal studies	Expand across climates	[119]
MM occupant perceptions	Limited surveys	Larger sample sizes needed	[58]
Dynamic response metrics standardization	Current lack of unified metric	Adopt response-time framework for ESS/TABS	[98]
Automation vs occupant adaptation	Automated MM reduces adaptive responses	Further studies on balancing automation with user control	[91]
Simulation-based control validation	Lab tests only	Expand to real buildings with diverse climates	[107]
Adaptive comfort model replication	Field evidence limited	Apply adaptive control in broader climates	[96]
Adaptive comfort range	Limited climates tested	Fieldwork in diverse geographies	[124]
Underground workspace	Few case studies	More pilot studies with health tracking	[125]
DSF-BIPV optimization	Limited façade types tested	Test with diverse climates and façade forms	[106]
Wind-driven NV	Orientation impacts critical	Extend CFD to diverse building types	[103]
Predictive MM HVAC	Few real deployments	Field validation in varied climates	[109]

CHP + TES integration	Urban decarbonisation tool	Pilot in multiple cities	[84]
Radiant HVAC	Limited validation	Expand field testing to offices/schools	[111]
Capillary ceilings	Emerging research	Study across seasons	[47]
Underground spaces	Design trade-offs unclear	Investigate lighting + IAQ impacts	[126]
Ventilation savings	Climate-dependence strong	Cross-climate comparative studies	[112]
Natural ventilation	Mostly residential focus	Extend to hospitals, schools	[48]
Comfort & IAQ studies	Single building focus	Multi-building comparative trials	[59]
AI prediction lacks generalization	Trained on limited regional datasets	Cross-region validation & uncertainty analysis	[85]
Hybrid PV–H_2 economics uncertain	Capital costs remain high	Long-term pilots & cost projections	[53]
Forecasting models site-specific	Need for wider validation	Multi-climate testing & benchmarking	[86]
Reduced-order model limitations	Accuracy vs. complexity trade-off unclear	Standardized benchmarks across climates	[131]
BIPV modelling	Barriers in cost/policy	Need wider adoption strategies	[132]
Retrofit modelling	Limited case studies	Apply ML retrofits to diverse climates	[60]
5G smart buildings	Early-stage adoption	Deploy at larger scales	[99]
Energy crisis strategies	Crisis-driven only	Long-term integration policies	[100]
SPDI HVAC model	Single test site	Validate in multiple commercial sites	[39]
NZEB integration	Few hybrid case studies	Pilot hybrid RE systems widely	[101]
AI EMS scalability	Tested in limited pilots	Deploy at city/district scale	[61]
BIM + Point cloud	Integration still costly	Standardize IFC extensions	[133]
ML prediction	Limited datasets	Expand to diverse climates & buildings	[92]
HRES reliability vs cost	Trade-offs context-specific	Include demand response & thermal storage in sizing	[134]
Model simplification standards	No common error/run-time targets	Benchmark studies across climates & typologies	[62]
AI for BEMS generalization	Data scarcity & bias	Open datasets; robust ML with uncertainty quantification	[83]

Hybrid RES	Mostly simulation studies	Expand to field pilots	[54]
Energy sharing	Limited urban pilots	Deploy at city-scale	[64]
Policy drivers	Unclear in some economies	Cross-country comparative studies	[137]

References:

1. Hu, M. and N.W. Esram, *The Status of Embodied Carbon in Building Practice and Research in the United States: A Systematic Investigation.* Sustainability, 2021. **13**(23): p. 12961.
2. Noh, Y., P. Anand, and S. Jafarinejad, *A Review on Harnessing Renewable Energy Synergies for Achieving Urban Net-Zero Energy Buildings: Technologies, Performance Evaluation, Policies, Challenges, and Future Direction.* Sustainability, 2024. **16**(8): p. 3444.
3. Peng, Y., et al., *Hybrid system controls of natural ventilation and HVAC in mixed-mode buildings: A comprehensive review.* Energy and Buildings, 2022. **276**: p. 112509.
4. Emami Javanmard, M., S.F. Ghaderi, and M.S. Sangari, *Integrating energy and water optimization in buildings using multi-objective mixed-integer linear programming.* Sustainable Cities and Society, 2020. **62**: p. 102409.
5. Bi, C. and J.C. Little, *Integrated assessment across building and urban scales: A review and proposal for a more holistic, multi-scale, system-of-systems approach.* Sustainable Cities and Society, 2022. **82**: p. 103915.
6. Perera, I., et al. *Combining Energy Performance and Indoor Environmental Quality (IEQ) in Buildings: A Systematic Review on Common IEQ Guidelines and Energy Codes in North America*. Energies, 2025. **18**, DOI: 10.3390/en18071740.
7. Rumbayan, M., et al., *Integration of smart water management and photovoltaic pumping system to supply domestic water for rural communities.* Results in Engineering, 2025. **25**: p. 103966.
8. Pradhan, S., S.G. Al-Ghamdi, and H.R. Mackey, *Greywater recycling in buildings using living walls and green roofs: A review of the applicability and challenges.* Science of The Total Environment, 2019. **652**: p. 330-344.
9. Relich, M., *Renewable energy in the European Union: The state of the art and directions of development.* WSEAS Transactions on Business and Economics, 2024. **21**: p. 630-637.
10. Obergassel, W., et al., *Phoenix from the ashes: an analysis of the Paris Agreement to the United Nations Framework Convention on Climate Change; part 1.* 2015.
11. Assembly, U.G., *Transforming our world: the 2030 Agenda for Sustainable Development.* 2015.
12. Outlook, I.E., *International Energy Agency (IEA), 2021*. 2021.
13. Nazari-Heris, M., *Natural Energy, Lighting, and Ventilation in Sustainable Buildings*. 2024: Springer.
14. Tamoor, M., et al., *Photovoltaic distributed generation integrated electrical distribution system for development of sustainable energy using reliability assessment indices and levelized cost of electricity.* Environmental Progress & Sustainable Energy, 2022. **41**(4): p. e13815.

15. Heussen, K., et al., *Unified system-level modeling of intermittent renewable energy sources and energy storage for power system operation.* IEEE Systems Journal, 2011. **6**(1): p. 140-151.
16. Mustafa, R., et al. *Solar insolation and PV module temperature impact on the actual grid connected solar photovoltaic system in German Malaysian Institute*. in *IOP Conference Series: Earth and Environmental Science*. 2023. IOP Publishing.
17. He, J., et al., *Reliability modeling and evaluation of urban multi-energy systems: A review of the state of the art and future challenges.* IEEE Access, 2020. **8**: p. 98887-98909.
18. Einan, M., H. Torkaman, and M. Pourgholi, *Optimized fuzzy-cuckoo controller for active power control of battery energy storage system, photovoltaic, fuel cell and wind turbine in an isolated micro-grid.* Batteries, 2017. **3**(3): p. 23.
19. Vikraman, V.K., P. D, and M. Ramasamy, *Performance Analysis of 3 kWp Rooftop Grid-connected Solar Photovoltaic System in an Urban House of Southern India.* Journal of Agricultural Engineering (India), 2020. **57**: p. 56-62.
20. Zadeh, S., et al., *Local area greywater symbiosis approach to a more sustainable urban water management*, in *The Sustainable World*. 2010, WIT Press Southampton, UK. p. 193-203.
21. Habibullah, N., S. Sahrir, and Z. Ponrahono, *Integrating rainwater harvesting and greywater recycling to increase water efficiency in office buildings.* Planning Malaysia, 2023. **21**.
22. Hourlier, F., et al., *Membrane process treatment for greywater recycling: investigations on direct tubular nanofiltration.* Water science and technology, 2010. **62**(7): p. 1544-1550.
23. Bouramdane, A.-A., *Optimal water management strategies: paving the way for sustainability in smart cities.* Smart Cities, 2023. **6**(5): p. 2849-2882.
24. Davidsson, H., R. Bernardo, and B. Hellström, *Hybrid ventilation with innovative heat recovery—a system analysis.* Buildings, 2013. **3**(1): p. 245-257.
25. Turner, W.J. and I.S. Walker, *Using a ventilation controller to optimise residential passive ventilation for energy and indoor air quality.* Building and Environment, 2013. **70**: p. 20-30.
26. Rasheed, E.O. and J.O.B. Rotimi, *The green office environment: New Zealand workers' perception of IEQ.* Smart and Sustainable Built Environment, 2024. **13**(5): p. 1240-1259.
27. Soudian, S. and U. Berardi, *Assessing the effect of night ventilation on PCM performance in high-rise residential buildings.* Journal of Building Physics, 2019. **43**(3): p. 229-249.
28. Cao, G., et al., *A review of the performance of different ventilation and airflow distribution systems in buildings.* Building and environment, 2014. **73**: p. 171-186.
29. Soebiyan, V., M. Koerniawan, and S. Triyadi. *A review of hybrid ventilation on humid tropics climate*. in *IOP conference series: earth and environmental science*. 2023. IOP Publishing.
30. Wang, H., et al., *An integrated approach to supporting land-use decisions in site redevelopment for urban renewal in Hong Kong.* Habitat International, 2013. **38**: p. 70-80.
31. Schuetze, T., J. Lee, and T. Lee, *Sustainable urban (re-) development with building integrated energy, water and waste systems. Sustainability 5 (3): 1114–1127*. 2013.
32. Panchalingam, R. and K.C. Chan, *A state-of-the-art review on artificial intelligence for Smart Buildings.* Intelligent Buildings International, 2021. **13**(4): p. 203-226.

33. Wu, R., G. Mavromatidis, and K. Orehounig. *Reliability optimisation of a district multi-energy system*. in *19. Status-Seminar" Forschen für den Bau im Kontext von Energie und Umwelt"*. 2016. ETH Zurich.
34. Martin, M., T. Weidner, and C. Gullström, *Estimating the potential of building integration and regional synergies to improve the environmental performance of urban vertical farming.* Frontiers in Sustainable Food Systems, 2022. **6**: p. 849304.
35. Han, K. and J. Zhang, *Energy-saving building system integration with a smart and low-cost sensing/control network for sustainable and healthy living environments: Demonstration case study.* Energy and Buildings, 2020. **214**: p. 109861.
36. Barbadilla-Martín, E., et al., *Assessment of thermal comfort and energy savings in a field study on adaptive comfort with application for mixed mode offices.* Energy and Buildings, 2018. **167**: p. 281-289.
37. Harrouz, J.P., et al., *Feasibility of MOF-based carbon capture from indoor spaces as air revitalization system.* Energy and Buildings, 2022. **255**: p. 111666.
38. Baus, L. and S. Nehr, *Potentials and limitations of direct air capturing in the built environment.* Building and Environment, 2022. **208**: p. 108629.
39. Coffman, A.R. and P. Barooah, *Simultaneous identification of dynamic model and occupant-induced disturbance for commercial buildings.* Building and Environment, 2018. **128**: p. 153-160.
40. Liang, R. and P.-H. Wang, *Enhancing energy efficiency in buildings, optimization method and building management systems application for lower CO2 emissions.* Energy, 2024. **313**: p. 134054.
41. Sharifi, M., et al., *A heuristic algorithm for optimal load splitting in hybrid thermally activated building systems.* Journal of Building Engineering, 2022. **50**: p. 104160.
42. Li, Z. and J. Zhang, *Study of distributed model predictive control for radiant floor heating systems with hydraulic coupling.* Building and Environment, 2022. **221**: p. 109344.
43. Akram, M.W., et al. *Global Prospects, Advance Technologies and Policies of Energy-Saving and Sustainable Building Systems: A Review*. Sustainability, 2022. **14**, DOI: 10.3390/su14031316.
44. Tushar, Q., et al., *An integrated approach of BIM-enabled LCA and energy simulation: The optimized solution towards sustainable development.* Journal of Cleaner Production, 2021. **289**: p. 125622.
45. Weber, R.E., C. Mueller, and C. Reinhart, *Solar exoskeletons – An integrated building system combining solar gain control with structural efficiency.* Solar Energy, 2022. **240**: p. 301-314.
46. Huang, H., et al., *Synergistic approach of energy generation and conservation in buildings exploiting semitransparent organic photovoltaic windows globally.* Nano Energy, 2025: p. 111181.
47. Jing, Z. and L. Jiayu, *Study on heat transfer delay of exposed capillary ceiling radiant panels (E-CCRP) system based on CFD method.* Building and Environment, 2020. **180**: p. 106982.
48. Pisello, A.L., et al., *The impact of natural ventilation on building energy requirement at inter-building scale.* Energy and Buildings, 2016. **127**: p. 870-883.
49. Liu, K., B. Zhu, and J. Chen *Low-Carbon Design Path of Building Integrated Photovoltaics: A Comparative Study Based on Green Building Rating Systems*. Buildings, 2021. **11**, DOI: 10.3390/buildings11100469.
50. Zhang, X., Y. Ge, and R.V. Patel, *Renewable Energy Integration and Energy Efficiency Enhancement for a Net-Zero-Carbon Commercial Building.* Buildings, 2025. **15**(3): p. 414.

51. Zhang, J., et al., *Research and Case Application of Zero-Carbon Buildings Based on Multi-System Integration Function.* Buildings, 2024. **14**(11): p. 3394.
52. Kachalla, I.A. and C. Ghiaus. *Forecasting hot water consumption demand for residential dwellings using hybrid regression technique*. in *2024 IEEE International Conference on Green Energy and Smart Systems (GESS)*. 2024. IEEE.
53. Mokhtara, C., et al., *Design optimization of grid-connected PV-Hydrogen for energy prosumers considering sector-coupling paradigm: Case study of a university building in Algeria.* International Journal of Hydrogen Energy, 2021. **46**(75): p. 37564-37582.
54. Das, M., M.A.K. Singh, and A. Biswas, *Techno-economic optimization of an off-grid hybrid renewable energy system using metaheuristic optimization approaches–case of a radio transmitter station in India.* Energy conversion and management, 2019. **185**: p. 339-352.
55. Hadengue, B., E. Morgenroth, and T.A. Larsen, *How to get your feet wet: Integrating urban water and building engineering for low-energy domestic hot water systems.* Energy and Buildings, 2022. **271**: p. 112318.
56. Kachalla, I.A., C. Ghiaus, and M. Baseer, *Comparative analysis of machine learning models for prediction and forecasting of electric water boilers energy consumption.* Applied Thermal Engineering, 2025. **267**: p. 125799.
57. Liu, J., et al., *Analysis of user behavior and energy-saving potential of electric water heaters.* Energy Informatics, 2024. **7**(1): p. 114.
58. Kim, J., et al., *Thermal comfort in a mixed-mode building: Are occupants more adaptive?* Energy and Buildings, 2019. **203**: p. 109436.
59. Junghans, L. and P. Widerin, *Thermal comfort and indoor air quality of the "Concept 22/26", a new high performance building standard.* Energy and Buildings, 2017. **149**: p. 114-122.
60. Deb, C. and A. Schlueter, *Review of data-driven energy modelling techniques for building retrofit.* Renewable and Sustainable Energy Reviews, 2021. **144**: p. 110990.
61. Rocha, H.R., et al., *An Artificial Intelligence based scheduling algorithm for demand-side energy management in Smart Homes.* Applied Energy, 2021. **282**: p. 116145.
62. Qu, K., et al., *Comparison analysis on simplification methods of building performance optimization for passive building design.* Building and Environment, 2022. **216**: p. 108990.
63. Zocchi, G., M. Hosseini, and G. Triantafyllidis, *Exploring the synergy of advanced lighting controls, building information modelling and internet of things for sustainable and energy-efficient buildings: A systematic literature review.* Sustainability, 2024. **16**(24): p. 10937.
64. Murphy, A.R. and A.S. Fung, *Techno-economic study of an energy sharing network comprised of a data centre and multi-unit residential buildings for cold climate.* Energy and Buildings, 2019. **186**: p. 261-275.
65. Sampsel, L.J., *Voyant tools.* Music Reference Services Quarterly, 2018. **21**(3): p. 153-157.
66. Zheng, Y., et al., *Research Progress and Development Trends of Building Energy Conservation Based on Bibliometric Analysis.* IET Renewable Power Generation, 2025. **19**(1): p. e70035.
67. Kabre, C., *Synergistic Design of Sustainable Built Environments*. 2020: CRC Press.
68. Lumpkin, D.R., W.T. Horton, and J.V. Sinfield, *Holistic synergy analysis for building subsystem performance and innovation opportunities.* Building and Environment, 2020. **178**: p. 106908.
69. Fanger, P.O., *Thermal comfort: analysis and applications in environmental engineering.* Perspect Public Health, 1970. **92**: p. 164.

70. Frontczak, M. and P. Wargocki, *Literature survey on how different factors influence human comfort in indoor environments.* Building and environment, 2011. **46**(4): p. 922-937.
71. Yang, X., et al., *Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China.* Journal of Cleaner Production, 2018. **183**: p. 729-743.
72. Li, D., P. Cui, and Y. Lu, *Development of an automated estimator of life-cycle carbon emissions for residential buildings: A case study in Nanjing, China.* Habitat International, 2016. **57**: p. 154-163.
73. Hu, F. and X. Zheng, *Carbon Emission of Energy Efficient Residential Building.* Procedia Engineering, 2015. **121**: p. 1096-1102.
74. Shen, K., L. Ding, and C.C. Wang, *Development of a Framework to Support Whole-Life-Cycle Net-Zero-Carbon Buildings through Integration of Building Information Modelling and Digital Twins.* Buildings, 2022. **12**(10): p. 1747.
75. Li, L., *Integrating climate change impact in new building design process: A review of building life cycle carbon emission assessment methodologies.* Cleaner Engineering and Technology, 2021. **5**: p. 100286.
76. Thilker, C.A., et al., *Non-linear grey-box modelling for heat dynamics of buildings.* Energy and Buildings, 2021. **252**: p. 111457.
77. Chong, A., Y. Gu, and H. Jia, *Calibrating building energy simulation models: A review of the basics to guide future work.* Energy and Buildings, 2021. **253**: p. 111533.
78. Du, Q., et al., *Dynamic integrated simulation of carbon emission reduction potential in China's building sector.* Sustainable Cities and Society, 2024. **116**: p. 105944.
79. Wang, D. and Y. Lin, *A comprehensive review on definitions, development, and policies of net-zero carbon buildings (nZCBs).* Renewable and Sustainable Energy Reviews, 2025. **217**: p. 115750.
80. Xiong, Z., et al., *Stochastic planning for low-carbon building integrated energy system considering electric-heat-V2G coupling.* International Journal of Electrical Power & Energy Systems, 2023. **151**: p. 109148.
81. Valencia, A., et al., *Synergies of green building retrofit strategies for improving sustainability and resilience via a building-scale food-energy-water nexus.* Resources, Conservation and Recycling, 2022. **176**: p. 105939.
82. Chen, L., et al., *Benefits and limitations of recycled water systems in the building sector: a review.* Environmental Chemistry Letters, 2024. **22**(2): p. 785-814.
83. Mehmood, M.U., et al., *A review of the applications of artificial intelligence and big data to buildings for energy-efficiency and a comfortable indoor living environment.* Energy and buildings, 2019. **202**: p. 109383.
84. Golafshani, S.R., M. Fatehpour, and E. Houshfar, *Optimization and dynamic techno-economic assessment of integrated combined ejector cooling, heating, and power system.* Energy, 2023. **282**: p. 128829.
85. Zhang, Y., et al., *Data-driven estimation of building energy consumption and GHG emissions using explainable artificial intelligence.* Energy, 2023. **262**: p. 125468.
86. Li, X., J. Wen, and E.-W. Bai, *Developing a whole building cooling energy forecasting model for on-line operation optimization using proactive system identification.* Applied Energy, 2016. **164**: p. 69-88.
87. Lydon, G.P., et al., *Coupled simulation of thermally active building systems to support a digital twin.* Energy and Buildings, 2019. **202**: p. 109298.

88. Hainoun, A., et al., *Smarter together: monitoring and evaluation of integrated building solutions for low-energy districts of lighthouse cities Lyon, Munich, and Vienna.* Energies, 2022. **15**(19): p. 6907.
89. Januário, M., et al., *Integrated Energy and Environmental Modeling to Design Cost-Effective Building Solutions at a Regional Level.* Energies, 2024. **17**(22): p. 5730.
90. Volkova, A., et al., *5th generation district heating and cooling (5GDHC) implementation potential in urban areas with existing district heating systems, Energy Rep. 8 (2022) 10037–10047*.
91. Khoshbakht, M., Z. Gou, and F. Zhang, *A pilot study of thermal comfort in subtropical mixed-mode higher education office buildings with different change-over control strategies.* Energy and Buildings, 2019. **196**: p. 194-205.
92. Wang, R., S. Lu, and W. Feng, *A novel improved model for building energy consumption prediction based on model integration.* Applied Energy, 2020. **262**: p. 114561.
93. Salcido, J.C., A.A. Raheem, and R.R. Issa, *From simulation to monitoring: Evaluating the potential of mixed-mode ventilation (MMV) systems for integrating natural ventilation in office buildings through a comprehensive literature review.* Energy and Buildings, 2016. **127**: p. 1008-1018.
94. Omrani, S., et al., *Natural ventilation in multi-storey buildings: Design process and review of evaluation tools.* Building and environment, 2017. **116**: p. 182-194.
95. Gil-Baez, M., et al., *Natural ventilation systems in 21st-century for near zero energy school buildings.* Energy, 2017. **137**: p. 1186-1200.
96. Barbadilla-Martín, E., et al., *Assessment of thermal comfort and energy savings in a field study on adaptive comfort with application for mixed mode offices.* Energy and Buildings, 2018. **167**: p. 281-289.
97. Mateus, N.M., et al., *Comparison of measured and simulated performance of natural displacement ventilation systems for classrooms.* Energy and Buildings, 2016. **133**: p. 185-196.
98. Ning, B., S. Schiavon, and F.S. Bauman, *A novel classification scheme for design and control of radiant system based on thermal response time.* Energy and Buildings, 2017. **137**: p. 38-45.
99. Huseien, G.F. and K.W. Shah, *A review on 5G technology for smart energy management and smart buildings in Singapore.* Energy and AI, 2022. **7**: p. 100116.
100. Farghali, M., et al., *Strategies to save energy in the context of the energy crisis: a review.* Environmental Chemistry Letters, 2023. **21**(4): p. 2003-2039.
101. Reddy, V.J., et al., *Pathway to sustainability: An overview of renewable energy integration in building systems.* Sustainability, 2024. **16**(2): p. 638.
102. Chen, B. and Y. Wang, *Short-term electric load forecasting of integrated energy system considering nonlinear synergy between different loads.* IEEE Access, 2021. **9**: p. 43562-43573.
103. Elshafei, G., et al., *Numerical and experimental investigations of the impacts of window parameters on indoor natural ventilation in a residential building.* Energy and Buildings, 2017. **141**: p. 321-332.
104. Lamnatou, C., et al., *Modelling and simulation of Building-Integrated solar thermal systems: Behaviour of the coupled building/system configuration.* Renewable and Sustainable Energy Reviews, 2015. **48**: p. 178-191.
105. Saadon, S., et al., *Simulation study of a naturally-ventilated building integrated photovoltaic/thermal (BIPV/T) envelope.* Renewable Energy, 2016. **87**: p. 517-531.

106. Agathokleous, R.A. and S.A. Kalogirou, *Double skin facades (DSF) and building integrated photovoltaics (BIPV): A review of configurations and heat transfer characteristics.* Renewable Energy, 2016. **89**: p. 743-756.
107. Moon, H., M. Choi, and K. An, *A simulation-based control approach in a mechanical ventilation system.* Proceedings of ASim, Shanghai, China, 2012.
108. Karami, M., G.V. McMorrow, and L. Wang, *Continuous monitoring of indoor environmental quality using an Arduino-based data acquisition system.* Journal of Building Engineering, 2018. **19**: p. 412-419.
109. Zhao, J., et al., *Occupant-oriented mixed-mode EnergyPlus predictive control simulation.* Energy and Buildings, 2016. **117**: p. 362-371.
110. Wang, G., et al., *Design and performance estimate of a novel linear fresnel reflector solar-gas combined system for producing electricity and hydrogen.* Renewable Energy, 2024. **227**: p. 120606.
111. Wang, Y., et al., *Study of an integrated radiant heating/cooling system with fresh air supply for household utilization.* Building and Environment, 2019. **165**: p. 106404.
112. Cuce, E., et al., *Sustainable ventilation strategies in buildings: CFD research.* Sustainable Energy Technologies and Assessments, 2019. **36**: p. 100540.
113. Mostafavi, F., M. Tahsildoost, and Z. Zomorodian, *Energy efficiency and carbon emission in high-rise buildings: A review (2005-2020).* Building and Environment, 2021. **206**: p. 108329.
114. Wu, M., et al., *Flexible Regulation and Synergy Analysis of Multiple Loads of Buildings in a Hybrid Renewable Integrated Energy System.* Sustainability, 2024. **16**(7): p. 2969.
115. Chang, C., C.-Y. Chen, and T.-P. Lin, *Combining geographic information and climate data to develop urban building energy prediction models in Taichung, Taiwan.* Sustainable Cities and Society, 2024. **117**: p. 105949.
116. Lopez-Garcia, E., et al., *Monitoring and analytics to measure heat resilience of buildings and support retrofitting by passive cooling.* Journal of Building Engineering, 2022. **57**: p. 104985.
117. Wang, Y., et al., *Optimized operation of integrated energy systems accounting for synergistic electricity and heat demand response under heat load flexibility.* Applied Thermal Engineering, 2024. **243**: p. 122640.
118. Yu, T., et al., *A novel system solution for cooling and ventilation in office buildings: A review of applied technologies and a case study.* Energy and Buildings, 2015. **90**: p. 142-155.
119. Deng, X., et al., *Thermal comfort evaluation of a mixed-mode ventilated office building with advanced natural ventilation and underfloor air distribution systems.* Energy Procedia, 2017. **111**: p. 520-529.
120. Zhao, G., et al., *Systemic boundaries in industrial systems: A new concept defined to improve LCA for metallurgical and manufacturing systems.* Journal of Cleaner Production, 2018. **187**: p. 717-729.
121. Howell, S., Y. Rezgui, and T. Beach, *Integrating building and urban semantics to empower smart water solutions.* Automation in Construction, 2017. **81**: p. 434-448.
122. Jiao, X., et al., *Electrical Power Interconnection-Based Urban Energy Systems: A Study of the Clean, Economic and Synergistic Operation.* Energy Science & Engineering, 2025. **13**(2): p. 657-672.
123. Homod, R.Z., K.S.M. Sahari, and H.A. Almurib, *Energy saving by integrated control of natural ventilation and HVAC systems using model guide for comparison.* Renewable Energy, 2014. **71**: p. 639-650.

124. Barbadilla-Martín, E., et al., *Field study on adaptive thermal comfort in mixed mode office buildings in southwestern area of Spain.* Building and Environment, 2017. **123**: p. 163-175.
125. Soh, C.-K., et al., *Human-centered development of underground work spaces.* Procedia engineering, 2016. **165**: p. 242-250.
126. Cao, S.-J., et al., *Sustainable underground spaces: Design, environmental control and energy conservation*. 2022, Elsevier. p. 111779.
127. Almansour, M. and M. Krarti, *Value engineering optimal design approach of high-performance residential buildings: Case study of Kuwait.* Energy and Buildings, 2022. **258**: p. 111833.
128. Hall, F. and R. Greeno, *Building services handbook*. 2023: Routledge.
129. Everard, M. and R. McInnes, *Systemic solutions for multi-benefit water and environmental management.* Science of the Total Environment, 2013. **461**: p. 170-179.
130. Deere, J.R., et al., *Occurrence of contaminants of emerging concern in aquatic ecosystems utilized by Minnesota tribal communities.* Science of the Total Environment, 2020. **724**: p. 138057.
131. Wang, J., et al., *Development and validation of a second-order thermal network model for residential buildings.* Applied Energy, 2022. **306**: p. 118124.
132. Kuhn, T.E., et al., *Review of technological design options for building integrated photovoltaics (BIPV).* Energy and Buildings, 2021. **231**: p. 110381.
133. Krijnen, T. and J. Beetz, *An IFC schema extension and binary serialization format to efficiently integrate point cloud data into building models.* Advanced Engineering Informatics, 2017. **33**: p. 473-490.
134. Muh, E. and F. Tabet, *Comparative analysis of hybrid renewable energy systems for off-grid applications in Southern Cameroons.* Renewable energy, 2019. **135**: p. 41-54.
135. Kachalla, I.A. and C. Ghiaus, *Electric Water Boiler Energy Prediction: state-of-the-art review of influencing factors, techniques, and future directions.* Energies, 2024. **17**(2): p. 443.
136. Wang, R., et al., *A modeling framework to examine photovoltaic rooftop peak shaving with varying roof availability: A case of office building in Hong Kong.* Journal of Building Engineering, 2021. **44**: p. 103349.
137. Zhao, J., et al., *The determinants of renewable energy sources for the fueling of green and sustainable economy.* Energy, 2022. **238**: p. 122029.
138. Ürge-Vorsatz, D., et al., *Heating and cooling energy trends and drivers in buildings.* Renewable and Sustainable Energy Reviews, 2015. **41**: p. 85-98.
139. Mahecha Zambrano, J., U. Filippi Oberegger, and G. Salvalai, *Towards integrating occupant behaviour modelling in simulation-aided building design: Reasons, challenges and solutions.* Energy and Buildings, 2021. **253**: p. 111498.
140. Gouveia, J.P. and P. Palma, *Harvesting big data from residential building energy performance certificates: retrofitting and climate change mitigation insights at a regional scale.* Environmental Research Letters, 2019. **14**(9): p. 095007.
141. Reynolds, J., et al., *Operational supply and demand optimisation of a multi-vector district energy system using artificial neural networks and a genetic algorithm.* Applied Energy, 2019. **235**: p. 699-713.
142. Choi, S. and S. Yoon *AI Agent-Based Intelligent Urban Digital Twin (I-UDT): Concept, Methodology, and Case Studies*. Smart Cities, 2025. **8**, DOI: 10.3390/smartcities8010028.

Figures



Figure 5

Illustrates the shifting research landscape of building-level E–W–V studies over the past decade (2015–2025), revealing four distinct phases in thematic progression.