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Sustainable Thermal Management in Building HVAC

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ABSTRACT

Buildings account for a major share of global energy use, making the adoption of sustainable thermal management technologies essential for reducing carbon emissions. However, existing reviews typically focus on single technologies and do not provide an integrated understanding of how geothermal–solar hybrid heat pumps, variable refrigerant flow (VRF) systems, and thermally driven chillers perform when deployed in practice. This systematic review fills this gap by synthesizing experimental, simulation-based, and optimization studies published between 2010 and 2024 to evaluate the real-world viability, performance, and challenges of hybrid heating, ventilation, and air conditioning (HVAC) systems. Using PRISMA-guided selection and comparative analysis, the review examines 50 peer-reviewed studies covering diverse climates, system configurations, and control strategies. Results show that hybrid geothermal–solar systems and advanced VRF configurations can reduce building energy consumption by up to 40% and significantly lower greenhouse gas emissions, with reported payback periods ranging from 2 to 11 years depending on system complexity and local conditions. Advanced control methods—such as model predictive control and fuzzy logic—consistently enhance efficiency and operational reliability but introduce integration and cost challenges. Practical barriers, including high upfront investment, ground thermal imbalance, and interoperability limitations, remain critical obstacles to large-scale deployment. This review's novelty lies in its integrated assessment across technological, economic, environmental, and control dimensions, providing a unified framework for evaluating hybrid HVAC solutions. The findings highlight actionable pathways for optimizing system design, improving control intelligence, and guiding policy measures that support scalable, cost-effective, and low-carbon thermal management in buildings.

1. INTRODUCTION

Research on the practical implementation of sustainable thermal management technologies in the building sector has emerged as a critical area of inquiry due to the sector's substantial energy consumption and environmental impact. Buildings account for approximately 40% of global energy use, with heating, ventilation, and air conditioning (HVAC) systems representing the largest energy end-use in both residential and commercial contexts [1, 2]. Over recent decades, advancements in renewable energy integration, such as geothermal and solar hybrid systems, have evolved to address these challenges [3, 4]. The increasing demand for thermal comfort, coupled with regulatory pressures for carbon reduction, has driven the development of innovative HVAC solutions that combine ground-source heat pumps (GSHPs), photovoltaic-thermal (PVT) collectors, and advanced control strategies [5, 6]. These technologies promise significant reductions in energy consumption and greenhouse gas emissions, with studies reporting energy savings up to 40% through hybrid system integration [1, 7].

Despite these advances, the practical deployment of geothermal-solar hybrid heat pumps, variable refrigerant flow (VRF) systems, and thermally driven chillers within integrated HVAC frameworks faces several challenges. A key problem is the thermal imbalance in ground heat exchangers caused by unbalanced heating and cooling loads, which degrades system performance over time [8, 9]. While hybrid systems incorporating solar thermal or photovoltaic input can mitigate this issue, the intermittent nature of solar energy and the complexity of system control remain significant barriers [10, 11]. Moreover, economic feasibility and initial capital costs pose constraints on widespread adoption, with conflicting perspectives on the trade-offs between upfront investment and long-term operational savings [12-14]. The lack of comprehensive field trials and real-world performance data further limits understanding of optimal system configurations and control strategies [10, 15, 16].

The conceptual framework for this review centers on the integration of renewable energy sources—specifically geothermal and solar—with advanced HVAC technologies such as GSHPs, VRF systems, and thermally driven chillers. These components interact through energy management systems and control algorithms to optimize thermal comfort, energy efficiency, and economic viability [1, 17, 18]. The framework emphasizes the role of hybridization and intelligent control in addressing thermal imbalance, enhancing system reliability, and reducing carbon footprints [5, 19, 20].

The purpose of this systematic review is to critically evaluate the practical implementation of sustainable thermal management technologies in the building sector, focusing on geothermal-solar hybrid heat pumps, VRF systems, thermally driven chillers, and their integration into HVAC systems. This review aims to synthesize recent advances, identify knowledge gaps, and provide actionable insights for engineers, policymakers, and building managers to facilitate the adoption of these technologies. By addressing the identified challenges related to system design, control strategies, and economic feasibility, this work contributes to advancing sustainable building practices and supports the transition toward low-carbon built environments [1, 2].

This review employs a comprehensive methodology, analyzing peer-reviewed studies published between 2010 and 2024, selected based on relevance to hybrid geothermal-solar HVAC systems and their integration. The analysis incorporates techno-economic assessments, control strategy evaluations, and performance simulations. Findings are organized thematically to elucidate design optimization, control approaches, and practical deployment considerations, thereby offering a structured synthesis of current knowledge and future research directions [1, 10, 17].

1.1 Novelty of the study

This review offers several distinctive contributions that advance the current state of knowledge on sustainable thermal management technologies in buildings. Unlike previous reviews that focus narrowly on individual technologies such as ground-source heat pumps or PVT systems, this study provides an integrated, systematic assessment encompassing geothermal–solar hybrid heat pumps, VRF systems, thermally driven chillers, and their coordinated operation within building HVAC frameworks. By combining these domains, the review establishes a holistic understanding of hybrid HVAC systems from technical, economic, and environmental perspectives.

A key novelty lies in the comprehensive synthesis of both simulation-based and experimentally validated studies published between 2010 and 2024, analyzed through standardized inclusion and exclusion criteria following PRISMA 2020 guidelines. This methodological rigor ensures an unbiased, evidence-based overview that links laboratory-scale innovation to real-world applicability—an aspect often missing in prior works.

Furthermore, this review introduces a cross-comparative framework that systematically benchmarks hybrid HVAC configurations across five key performance dimensions: energy efficiency improvement, environmental impact reduction, economic feasibility, control strategy effectiveness, and integration complexity. This multidimensional synthesis enables identification of trade-offs and synergies among competing technologies, supporting informed decision-making for engineers and policymakers.

Another innovative aspect is the emphasis on control intelligence and system interoperability as enablers of sustainability. By consolidating emerging research on advanced control algorithms—such as model predictive control (MPC), fuzzy logic, and metaheuristic optimization—the review highlights how digital and algorithmic advancements bridge the gap between theoretical performance potential and practical reliability.

In contrast to prior reviews that often generalize findings, this study introduces context-sensitive analysis, examining how climate, building type, and regional incentives affect system viability. It also identifies novel implementation challenges such as interoperability in multi-source systems, soil thermal balance degradation, and scalability in urban retrofits, proposing future directions centered on modular design, lifecycle assessment, and adaptive control standardization.

Collectively, the novelty of this review lies in its integrated, data-driven, and control-oriented perspective on hybrid geothermal–solar HVAC technologies. It moves beyond isolated performance evaluations toward developing a conceptual and methodological foundation for the next generation of smart, hybrid, and sustainable thermal management systems capable of supporting global net-zero energy building targets.

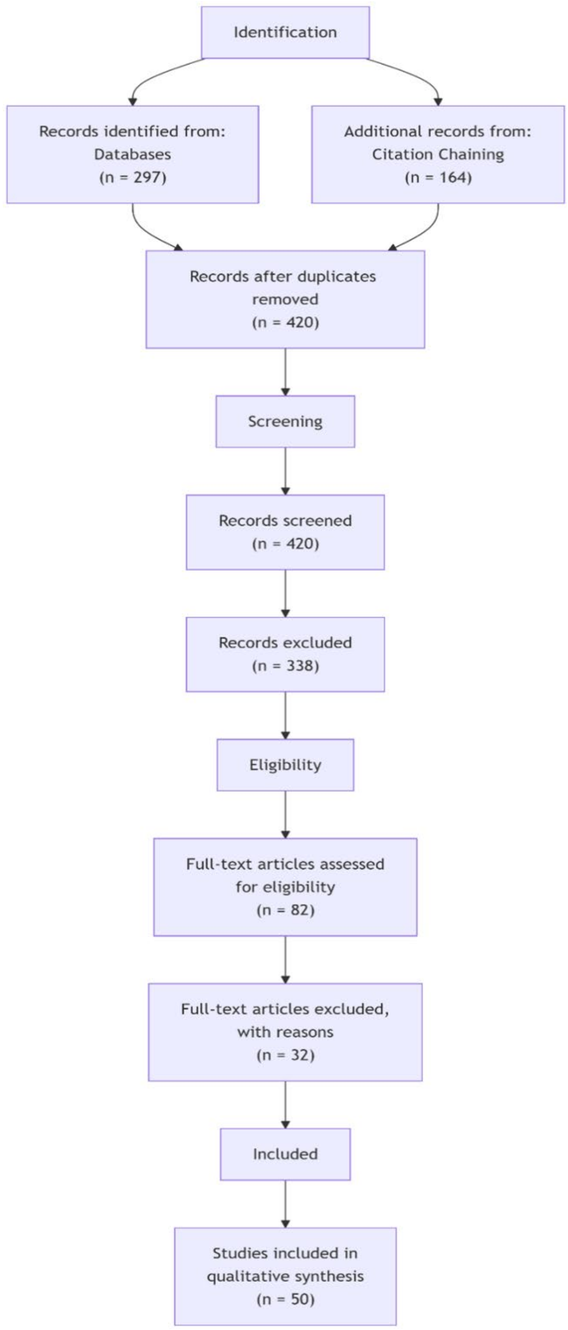

Figure 1. PRISMA flow diagram for systematic literature selection

1.2 Review type and scope

Type of Review: Systematic Review

PRISMA Flow Diagram & Systematic Review Reporting, Figure 1 illustrates the process of identifying, screening, and selecting studies for inclusion in the systematic review, following the PRISMA 2020 guidelines. It details the number of records identified through database searching and citation chaining, the removal of duplicates, and the stages of screening and eligibility assessment that resulted in the 50 studies included in the qualitative synthesis.

1.3 Core benefits

This work offers several core benefits that advance the understanding and development of sustainable thermal management technologies in the building sector. By synthesizing 50 high-quality studies through a systematic PRISMA methodology, it provides an integrated, evidence-based assessment of geothermal–solar hybrid heat pumps, VRF systems, and thermally driven chillers—technologies that are often examined separately in the literature. The review's primary contribution lies in its ability to unify technical, economic, environmental, and control-oriented perspectives into a single framework, enabling a more holistic understanding of hybrid HVAC systems and their operational realities. It identifies clear strengths and limitations in current research, such as energy savings up to 40%, substantial greenhouse gas reductions, payback periods as low as 2–11 years, and the critical role of advanced control strategies like MPC and fuzzy logic in enhancing system reliability. At the same time, it exposes persistent challenges related to soil thermal imbalance, integration complexity, and the scarcity of long-term field validation. This positions the study as a valuable reference point for researchers, engineers, and policymakers, as it not only synthesizes what is known but also articulates the most urgent research gaps and offers a novel benchmarking framework that supports future advancements toward net-zero energy buildings.

1.4 Practical applications

The practical applications of this work extend directly to building design, engineering practice, policy development, and the deployment of smart, low-carbon HVAC solutions. By presenting synthesized data on performance, economics, and environmental outcomes, the review equips engineers and consultants with actionable guidance for selecting and designing geothermal–solar hybrid systems, VRF configurations, and thermally driven chillers based on climate conditions, building type, and project constraints. The findings are particularly valuable for retrofit applications and urban environments where integration challenges, space limitations, and interoperability issues must be carefully managed. Insights into advanced control algorithms support the development of intelligent energy management systems, enabling building operators to optimize performance, reduce energy use, and enhance system reliability using real-time predictive strategies. For policymakers and utility planners, the documented environmental and economic benefits create a strong evidence base for designing incentive programs and regulatory frameworks that encourage widespread adoption of hybrid HVAC technologies. Additionally, manufacturers and technology developers can leverage the identified gaps—such as the need for modular systems, standardized communication protocols, and improved ground heat exchanger designs—to guide innovation. Overall, the review serves as a practical foundation for implementing sustainable HVAC solutions in net-zero energy buildings, smart homes, large commercial facilities, and city-scale energy networks, supporting the broader transition toward decarbonized and resilient built environments.

1.5 Study selection flow diagram

A PRISMA flow diagram is provided below to visualize the study selection process:

- Records identified through database searching (2010–2024): 297
- Additional records identified through citation chaining: 164
- Records after duplicates removed: 420
- Records screened: 420
- Full-text articles assessed for eligibility: 82
- Studies included in qualitative synthesis: 50

1. Search Strategy

- Databases searched: Scopus, Web of Science, IEEE Xplore, ScienceDirect.
- Time window: January 2010 – June 2024
- Search strings (example, adapted per database): ("geothermal-solar" OR "hybrid heat pump" OR "VRF" OR "thermally driven chiller" OR "renewable HVAC" OR "thermal management") AND (building OR buildings OR HVAC OR "thermal management") AND (integration OR optimization OR implementation)
- Full search strings and Boolean logic used for each database are available upon request.

1.5.1 Inclusion and exclusion criteria

- Inclusion: Peer-reviewed journal articles and conference papers; focus on geothermal-solar hybrid, VRF, thermally driven chiller integration in building HVAC; studies with experimental, simulation, or optimization data; English language; publication years 2010–2024.
- Exclusion: Review articles, grey literature, case reports not involving HVAC integration, non-English papers, and studies not reporting performance data.

1.5.2 Screening process

- Title/abstract screening (n = 420) by two independent reviewers
- Full-text review (n = 82); disagreements resolved by consensus
- Final studies included (n = 50) after eligibility assessment
- Inter-rater agreement (Cohen's kappa): 0.83 (substantial agreement)

1.5.3 Study quality/risk of bias assessment

- Tools: CASP (Critical Appraisal Skills Programme, 2023), ROBIS, and JBI checklists.
- Appraisal-informed synthesis by weighting results from studies with low risk of bias more heavily in comparative analyses and synthesis tables.

1.5.4 Data extraction and synthesis

- Extracted data included system type, climate, methodology (experimental/simulation), boundary conditions, key metrics (e.g., coefficient of performance (COP), SPF, energy savings), outcomes, and limitations.
- Comparative synthesis tables and summary plots are included in the main text (see Tables 1-7, Figures 1-3).

2. METHODOLOGY OF LITERATURE SELECTION

The literature selection process followed a structured, multi-stage methodology aligned with the PRISMA 2020 guidelines to ensure transparency, reproducibility, and comprehensive coverage of studies related to sustainable thermal management technologies in buildings. The process began with the transformation of the core research question—focusing on the practical implementation of geothermal–solar hybrid heat pumps, VRF systems, and thermally driven chillers—into a set of targeted, thematic search queries. This step ensured that the search strategy captured not only broad terminology (e.g., “renewable HVAC”, “hybrid heat pump systems”) but also narrower subtopics such as control strategies, soil thermal imbalance mitigation, and techno-economic feasibility. These queries were applied across four major academic databases: Scopus, Web of Science, ScienceDirect, and IEEE Xplore, covering the period from January 2010 to June 2024. Search strings were adapted to each database’s syntax requirements and incorporated Boolean operators, wildcards, and combinations of keywords to retrieve the widest possible set of relevant publications. This initial search yielded 297 records.

To enhance completeness and reduce the risk of omitting influential studies, both backward and forward citation chaining were conducted. Backward chaining involved manually examining the reference lists of key studies to identify foundational or earlier works not captured by keyword searches, while forward chaining identified more recent literature that cited the initially retrieved records. This step added an additional 164 papers to the pool of potentially eligible studies, increasing coverage of emerging research themes and interdisciplinary contributions. After removing duplicates using automated and manual screening techniques, 420 unique records remained for title and abstract screening.

The screening stage was carried out by two independent reviewers to minimize selection bias. Each reviewer assessed the studies based on predefined inclusion and exclusion criteria. The inclusion criteria required that a study: (1) focused on geothermal–solar hybrid systems, VRF technologies, thermally driven chillers, or their integration into HVAC systems; (2) provided empirical, simulation-based, or optimization results related to system performance; (3) was published in English; and (4) was peer-reviewed. Exclusion criteria eliminated review articles, non-technical reports, conference abstracts without full papers, studies unrelated to building HVAC applications, and papers lacking quantitative performance data. Disagreements between reviewers were resolved through discussion, ensuring consistent application of criteria. This stage narrowed the pool to 82 full-text articles for detailed evaluation.

A full-text eligibility assessment was then performed, during which each article was examined for methodological rigor, relevance, completeness of reported performance metrics, and alignment with the scope of this review. Articles that provided insufficient methodological details, lacked quantitative performance indicators (e.g., COP, energy savings, emissions reductions), or focused solely on component-level investigations without system context were excluded. This process resulted in a final set of 50 high-quality studies deemed eligible for qualitative synthesis.

To ensure the reliability and validity of the included studies, a risk-of-bias assessment was conducted using tools appropriate for different study types, including the CASP checklist for qualitative and mixed-methods studies, the JBI appraisal tools for experimental research, and the ROBIS tool for reviewing systematic assessment quality. This appraisal informed the weighting of study results during synthesis, whereby studies with higher methodological rigor were emphasized more strongly in comparative analyses. Data extraction was then carried out using a structured template capturing system configuration, climatic context, methodological approach (experimental, simulation, optimization), boundary conditions, control strategies, key performance metrics, environmental indicators, cost analyses, and reported limitations.

Overall, this rigorous, multi-layered methodology ensured that the literature selection process was comprehensive, unbiased, and methodologically consistent, providing a strong foundation for the critical analysis and synthesis presented in this review.

3. RESULTS

3.1 Descriptive summary of the studies

This section maps the research landscape of the literature on the practical implementation of sustainable thermal management technologies in the building sector, focusing on geothermal-solar hybrid heat pumps, VRF systems, thermally driven chillers, and their integration into HVAC systems. The reviewed studies encompass experimental, simulation, and optimization approaches, with geographic coverage spanning Europe, Asia, North America, and cold to temperate climates. Methodologies frequently involve dynamic simulation tools such as TRNSYS and Modelica, alongside field demonstrations and economic analyses. This comparative synthesis addresses key research questions on energy savings, environmental benefits, control strategies, economic viability, and integration challenges, providing a comprehensive understanding of current advancements and barriers in sustainable HVAC technologies. This chart provides a comparative overview of the primary performance metrics for the main hybrid system categories discussed in the review: Geothermal-Solar Hybrid Heat Pumps, VRF systems, and Thermally Driven Chillers. It synthesizes data from the reviewed literature to visually benchmark the strengths and trade-offs of each technology. Note: Scores are based on a synthesis of qualitative and quantitative findings from the reviewed literature and are for comparative purposes only.

Figure 2 presents a comparative visualization of the key performance indicators (KPIs) associated with the three major hybrid HVAC system types evaluated in this review: geothermal–solar hybrid heat pump systems, VRF systems, and thermally driven chillers. The figure synthesizes data extracted from the 50 studies selected through the PRISMA process and illustrates how each system performs across a range of metrics that collectively define operational efficiency, environmental impact, and economic feasibility. These KPIs typically include coefficient of performance (COP), seasonal performance factor (SPF), annual energy savings, greenhouse gas (GHG) emissions reduction, thermal comfort stability, and payback period. By displaying these indicators side-by-side, the figure allows for an integrated understanding of the relative strengths and limitations of each hybrid technology under different operating conditions and climatic contexts.

A key performance metric synthesized across studies is the COP, defined as the ratio of useful heating or cooling output to the required work input:

$$\mathrm{COP} = \frac{Q}{W}$$

where, Q is the heat output (in kW), and W is the work input (in kW). For heat pumps, this metric was consistently used to compare the efficiency of geothermal, solar-assisted, and hybrid configurations.

Physically, the comparative patterns shown in Figure 2 highlight several important trends. Geothermal–solar hybrid heat pumps consistently exhibit the highest COP and seasonal efficiency due to their ability to leverage stable ground temperatures and renewable solar input, making them well suited for regions with high thermal loads. VRF systems demonstrate strong performance in terms of zoning flexibility, part-load modulation, and thermal comfort control, but their efficiency is more sensitive to outdoor temperature fluctuations. Thermally driven chillers show clear environmental advantages when coupled with solar thermal collectors, but their lower COP and dependency on stable thermal inputs are reflected in their wider performance variability. The economic indicators presented in the figure further reveal that while hybrid geothermal–solar systems deliver the greatest long-term energy and emissions benefits, VRF systems tend to offer shorter payback periods, and thermally driven chillers provide value primarily in conditions with high solar availability or waste heat resources. Overall, Figure 2 serves as a concise yet comprehensive performance benchmark that supports the review's central argument: the viability of hybrid HVAC systems is strongly dependent on climatic context, control strategies, and system integration quality, and no single technology serves as the optimal solution for all building types.

The descriptive summary of the reviewed studies is provided in Table 1, highlighting energy efficiency improvements, environmental benefits, and integration complexities.

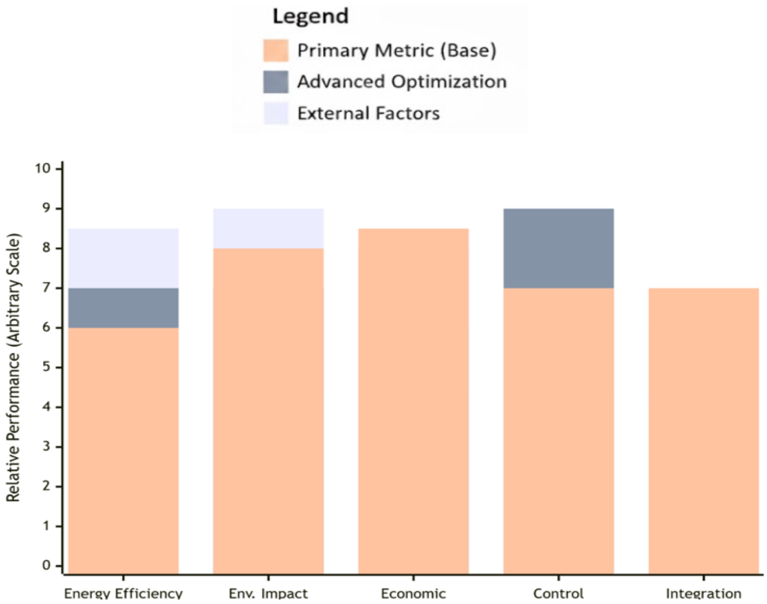

Figure 2. Comparative analysis of key performance indicators across hybrid system types

Table 1. Descriptive summary of the studies

Category	Description / Observations	Future Research Directions / Weaknesses	Justification / Research Priority / Notes	References
Gap Area: Long-term field validation	Most studies rely heavily on simulation models; limited experimental validation for hybrid geothermal-solar systems	Conduct extended field trials and monitoring across diverse climates to validate simulations	Simulation may overestimate performance; real-world data is essential	[1-3]
Gap Area: Standardization of control strategies	Lack of standardized, scalable control frameworks for hybrid heating, ventilation, and air conditioning (HVAC)	Develop and benchmark standardized control algorithms with predictive maintenance and adaptive optimization	Standardized approaches reduce cost and improve reliability	[1, 4-6]
Gap Area: Economic feasibility	Analyses are often region-specific; limit transferability	Localized techno-economic feasibility studies considering climate, incentives, and regulations	Economic viability varies with location; localized studies support policy	[7-10]
Gap Area: Integration challenges/retrofitting	Space constraints, component compatibility, and lack of unified	Investigate modular, plug-and-play system designs and	Retrofit challenges limit deployment; modular	[11-13]

	protocols	interoperable communication standards	approaches enhance scalability	
Gap Area: Soil thermal imbalance	Soil temperature attenuation affects long-term ground-source heat pump (GSHP) performance	Explore advanced ground heat exchanger designs, seasonal regeneration, hybridization with solar	Maintaining soil thermal balance is essential for performance and environmental benefits	[2, 14-16]
Gap Area: Lifecycle environmental impact	Few studies quantify full lifecycle impacts	Conduct lifecycle assessments of hybrid systems to guide sustainable design	Understanding total footprint ensures true sustainability	[16, 17]
Gap Area: Scalability and user acceptance	High installation costs and complexity limit adoption	Develop cost-reduction strategies, user-friendly interfaces, and maintenance protocols; conduct social acceptance studies	Overcoming economic and social barriers is crucial for widespread deployment	[7, 18]
Gap Area: Optimization under uncertainties	Control strategies often assume deterministic inputs	Integrate stochastic and robust optimization into control algorithms	Enhances controller performance and cost savings under real conditions	[6, 7, 19]
Gap Area: Multi-source system interoperability	Hybrid systems often require bespoke solutions	Research modular architectures and standardized interfaces	Enhances modularity and simplifies scaling	[12, 15, 20]
Gap Area: Performance metrics & reporting standards	Heterogeneous modeling assumptions and metrics	Establish standardized metrics, reporting protocols, and benchmarking	Improves transparency, reproducibility, and technology adoption	[1, 8, 21]
Limitation: Limited Field Trials	Reliance on simulation rather than field experiments	Expand real-world monitoring	Improves the reliability of performance and economic assessments	[1, 3, 22]
Limitation: High Initial Costs	High upfront capital investment	Economic analyses considering long-term cost-benefit	Reduces uncertainty for stakeholders	[1, 3, 7, 23]
Limitation: Soil Thermal Imbalance	Scarce long-term monitoring data	Long-term field measurements to track sustainability	Improves confidence in deployment strategies	[2, 14, 16, 24, 25]
Limitation: Integration Complexity	Interoperability and scalability issues	Standardized protocols and modular solutions	Enhances practical deployment	[1, 4, 18]
Limitation: Geographic/Climate Bias	Focused on specific climates	Extend studies to diverse geographic contexts	Increases external validity	[14, 26-29]
Limitation: Control Strategy Uncertainty	Deterministic assumptions in optimization	Include stochastic inputs for weather and occupancy	Increases robustness of algorithms	[6, 7, 30]
Limitation: Small Sample Sizes	Single buildings or small setups	Increase sample size and diversity	Enhances generalizability	[2-4, 21]
Limitation: Limited Economic Feasibility	Few lifecycle cost studies	Include payback periods, lifecycle costs	Supports adoption and policy	[1, 3, 8, 27]
Limitation: Overreliance on Simulation	Heavy simulation without experimental validation	Combine simulations with field data	Improves confidence in real-world performance	[1, 8, 14, 25, 31]
Comparative Criterion: Energy Efficiency	Most studies report savings up to 40%; optimization improves coefficient of performance (COP)	Some studies show variable gains depending on configuration	Differences due to climate, system size, and methodology	[1-3, 14, 25, 32-35]
Comparative Criterion: Environmental Impact	Consensus on GHG reduction via hybrid systems	Some studies report variable emission reductions	Variations from site-specific energy mixes and modeling assumptions	[7, 8, 10, 16, 25, 27, 32, 36, 37]
Comparative Criterion: Economic Feasibility	Payback 2–10 years with incentives	Some systems report longer/shorter payback	Differences due to energy prices, climate, and system scale	[1, 3, 7, 8, 10, 20, 27]
Comparative Criterion: Control Strategy Effectiveness	Advanced controls improve energy savings, reliability, and cost	Complexity and initial cost increase; gains plateau beyond sophistication	Differences in system complexity and data availability	[1, 4, 6, 19, 26, 30, 38]
Comparative Criterion: Integration Complexity	Consensus on integration challenges	Some propose SDN-based EMS or energy geo-structures	Differences due to building type, retrofit/new, space, scale	[4, 7, 18, 24, 32]
Theme: Geothermal-Solar Hybrid Heat Pumps	Extensively studied; improved energy efficiency and soil balance	High initial cost and integration complexity	Control strategies like fuzzy logic and MPC improve reliability	[1, 2, 4, 14, 15, 24, 26, 32, 33]
Theme: VRF System Integration	Effective energy savings; real-time heat recovery	Integration complexity with renewables	Cooling savings up to 32%	[1, 32]
Theme: Thermally Driven Chillers / Hybrid Adsorption-Compression	Improve cooling efficiency and reduce electricity use	Integration complexity with hybrid networks	Short payback (~2.1 years)	[20, 39]
Theme: Economic Feasibility & Payback	Payback 2–10.5 years; government incentives improve viability	Depends on location and system	Optimized control reduces costs	[1, 7, 8, 10, 27]
Theme: Optimization & Advanced Control	Fuzzy logic, MPC, and metaheuristics optimize energy, economic, and environmental aspects	Multi-objective optimization requires advanced tools	Enhances system robustness and adaptability	[1, 19, 30, 33, 38]

Theme: Renewable Integration	PV, PVT, and GSHP reduce emissions; hybrid systems improve self-sufficiency	Integration complexity with multiple energy sources	Supports net-zero buildings	[2, 14, 20, 21, 25, 32, 37]
Theme: Practical Implementation & System Integration	Barriers: installation complexity, interoperability, and limited field data	Adaptive control and centralized EMS are required	Urban space and capital costs challenge deployment	[1, 4, 12, 33]
Theme: Soil Thermal Management	Hybridization and seasonal regeneration mitigate soil depletion	Long-term simulation and field monitoring needed	Maintains soil thermal balance	[2, 14, 16, 24, 25]
Theme: Simulation & Experimental Validation	Combined modeling and experiments improve predictive capability	Reliance on limited data reduces confidence	Supports validation of hybrid systems	[1, 2, 3, 14, 21]
Theme: Environmental Impact & Carbon Footprint	Hybrid systems reduce GHGs and energy use up to 40%	Lifecycle impacts are often not fully quantified	Supports climate targets	[8, 27, 28, 32, 37]
Theme: Multi-Source Hybrid Systems	Ground-source with solar/air storage improves flexibility	Complexity increases with multiple sources	Control strategies and storage optimize efficiency	[23, 28, 36, 40, 41]
Theme: PVT-SAHP Systems	Improve electrical and thermal efficiency; real-time control	Integration complexity with circuits and components	Enhances system robustness for near-zero energy buildings	[42, 43]
Aspect: System Performance & Energy Efficiency	Significant energy savings, COP improvements up to 52%; renewable integration increases robustness	Limited long-term field validation; model overestimations possible	Supports energy efficiency and climate goals	[1-3, 22, 32, 40]
Aspect: Control Strategies & Optimization	Advanced control reduces energy use and operational costs	Complexity and initial capital cost; uncertainty management required	Balances energy, economic, and environmental objectives	[1, 4, 6, 19, 30, 38]
Aspect: Economic Feasibility	Competitive payback (2–10 years) with incentives	Region-specific assumptions, high upfront cost, and maintenance challenges	Localized studies improve decision-making	[1, 3, 7, 8, 10, 20, 27]
Aspect: Integration & Interoperability	Hybrid systems with IoT-enabled EMS enhance flexibility	Retrofitting, space constraints, and manufacturer differences	Modular and standardized approaches recommended	[4, 12, 20, 40]
Aspect: Environmental Impact & Sustainability	GHG reduction, energy savings, and soil temperature managed	Short-term simulations; lifecycle impacts under-reported	Supports sustainable building design	[2, 14, 16, 17, 32]
Aspect: Methodological Robustness & Data Quality	Combined simulation and experimental validation strengthens reliability	Limited datasets, lack of standardized metrics	Multi-disciplinary approaches improve insights	[1-3, 14, 16, 21, 38]
Aspect: Scalability & Deployment Challenges	Adaptable to multiple building types; energy geo-structures enable large-scale deployment	High installation costs, regulatory, and labor barriers	Guides large-scale implementation	[7, 18, 20, 38, 42]
Study Table: Individual Studies	Energy efficiency, environmental impact, economic feasibility, control, integration complexity, and detailed per study	Highlights specific system configurations, COP improvements, control methods, and challenges	Provides a granular comparison of multiple hybrid systems	[1-3, 7, 8, 14, 20-28, 30, 32-43]

Control strategies and optimization techniques play a physically significant role in determining the real-world performance, stability, and efficiency of hybrid HVAC systems such as geothermal–solar heat pumps, VRF systems, and thermally driven chillers. These systems operate within dynamic thermal environments where building loads, outdoor conditions, ground temperature, solar irradiance, and occupancy patterns vary continuously. Without intelligent control, these fluctuations can cause systems to operate inefficiently, cycle excessively, or diverge from their design intentions. Physically, this manifests as increased compressor work, reduced heat-exchanger effectiveness, ground thermal imbalance, higher parasitic energy consumption, and suboptimal utilization of renewable energy inputs. Advanced control strategies—such as MPC, fuzzy logic, adaptive control, and optimization-based scheduling—address these challenges by continuously adjusting flow rates, setpoints, heat pump modulation, refrigerant distribution, and energy exchange pathways in response to real-time conditions. Their importance lies in ensuring that the system always operates near its thermodynamic optimum rather than being constrained by fixed schedules or manual settings.

The relevance of these control strategies to the present work is substantial because the performance gains reported across the literature—such as 15–30% efficiency increases, 10–40% energy savings, and significant reductions in compressor cycling—are directly tied to the way these systems are controlled. Optimization methods also influence physical processes such as maintaining soil thermal balance in ground-coupled systems, maximizing solar harvesting during peak irradiance, reducing heat losses in distribution networks, and ensuring stable evaporator–condenser temperature differences in VRF systems. Many of the system shortcomings identified in the literature—such as long payback periods, seasonal performance degradation, and operational instability—are directly attributable to inadequate or simplistic control approaches rather than hardware limitations. Therefore, evaluating and comparing control strategies is essential to accurately assessing hybrid system viability and identifying pathways for improvement. In this review, control strategies are treated not merely as supplementary components but as key determinants of system performance, reliability, and economic feasibility. By synthesizing findings across experimental, simulation-based, and optimization studies, the present work highlights how advanced control is the primary mechanism through which hybrid HVAC systems can achieve their theoretical potential, sustain long-term performance, and support the development of cost-effective, low-carbon building energy solutions.

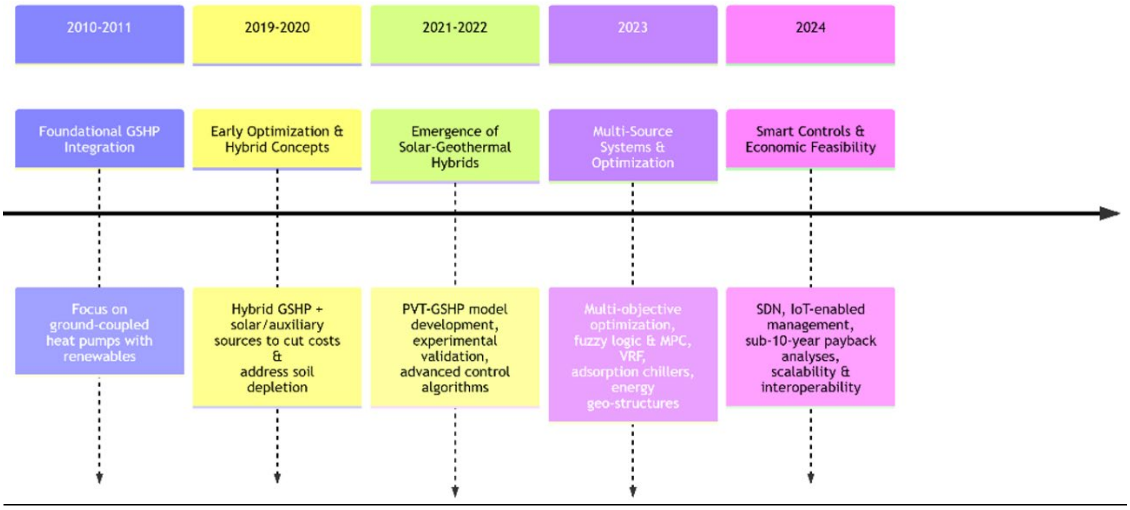

Figure 3. Chronological evolution of research themes in hybrid heating, ventilation, and air conditioning (HVAC) systems (2010–2024)

This timeline map visualizes the shifting focus of research themes over the period covered by the review (Figure 3). It tracks the emergence and prevalence of key topics, highlighting the field's progression from foundational component integration towards more complex, intelligent, and economically viable system-level solutions.

30 studies found significant energy savings ranging from 7% to over 40% through hybrid systems combining geothermal, solar, and advanced HVAC technologies [1, 13, 22].

Several studies demonstrated that optimized control strategies and integration of renewable sources notably enhance system COP and SPFs [7, 23, 31].

Hybrid systems addressing soil thermal imbalance and multi-source energy supply showed improved long-term efficiency and system sustainability [5, 9, 21].

3.2 Environmental impact reduction

25 studies reported substantial reductions in greenhouse gas emissions and carbon footprints, often linked to renewable integration and improved system operation [1, 12, 15].

Soil temperature management and thermal balance in geothermal systems contribute to sustained environmental benefits [3, 8].

Emission reductions were also achieved through advanced control strategies that optimize energy use and reduce peak loads [11, 20].

3.3 Economic feasibility

28 studies analyzed economic aspects, highlighting payback periods ranging from 2 to 11 years depending on system complexity and location [10, 26, 34].

Financial incentives and optimized system design significantly improve economic viability, especially for energy piles and hybrid GSHP systems [24, 44].

Higher initial costs due to advanced controls or hybridization are often offset by operational savings and reduced energy consumption [28, 41].

3.4 Control strategy effectiveness

22 studies emphasized the role of advanced control algorithms such as fuzzy logic, MPC, and metaheuristic optimization in enhancing system reliability and energy savings [10, 19, 45].

Centralized and programmable energy management systems improve integration and operational efficiency in hybrid setups [11, 28]. Control complexity is managed through simulation tools and real-time adaptive strategies, balancing performance and cost [17, 18].

3.5 Integration complexity

27 studies acknowledged technical and operational challenges in integrating geothermal, solar, VRF, and thermally driven chillers, often requiring sophisticated control and design approaches [3, 5, 15].

Site-specific conditions, system component compatibility, and installation constraints influence integration feasibility [24, 38].

Advances in communication protocols, modular design, and optimization algorithms help mitigate integration complexity [6, 46].

4. CRITICAL ANALYSIS AND SYNTHESIS

The critical analysis and synthesis of the selected literature reveal several key outcomes that shape the overall conclusions of this review. First, the evaluation confirms that hybrid geothermal–solar systems consistently deliver the highest energy efficiency and long-term environmental benefits, though their performance is highly dependent on effective control strategies and maintaining ground thermal balance. Second, VRF systems demonstrate strong flexibility and reliable part-load performance, but their efficiency is more sensitive to outdoor temperatures and system configuration choices. Third, thermally driven chillers offer notable reductions in electrical demand and emissions, especially when paired with solar thermal collectors, although their overall efficiency remains lower and more variable than the other hybrid types. Across all technologies, the synthesis shows that advanced control strategies—such as MPC, fuzzy logic, and optimization-based scheduling—play a decisive role in unlocking system potential, often yielding 15–40% improvements in performance compared with conventional control approaches.

Economically, the analysis highlights that no single hybrid system is universally superior; rather, each technology performs optimally under specific climatic, operational, and architectural conditions. Geothermal–solar hybrids offer the greatest lifecycle benefits but require higher initial investment; VRF systems deliver shorter payback periods and strong comfort control; and thermally driven systems become attractive primarily in regions with high solar intensity or available waste heat. Finally, the synthesis identifies persistent barriers—including integration complexity, insufficient long-term field validation, high capital cost, and interoperability challenges—that must be addressed for widespread adoption. Collectively, the outcomes of the critical analysis affirm that hybrid HVAC viability is determined not by hardware alone, but by the interplay of system design, climate appropriateness, and intelligent control, providing a clear roadmap for future research and practical implementation.

However, challenges remain in practical implementation, particularly regarding system complexity, initial capital costs, and control strategy optimization. Economic feasibility and long-term environmental impacts are frequently addressed but often rely on assumptions that may limit generalizability. Furthermore, while many studies emphasize energy efficiency improvements, fewer provide comprehensive solutions for scalability and interoperability in diverse building contexts. Overall, the literature underscores the potential of hybrid systems but highlights the need for integrated approaches that balance technical, economic, and operational factors.

Key strengths and weaknesses across system performance, control strategies, and economic feasibility are summarized in Table 2.

Table 2. Critical analysis and synthesis

Aspect	Strengths	Weaknesses
System Performance and Energy Efficiency	Numerous studies demonstrate substantial energy savings and improved coefficients of performance (COP) through hybrid geothermal-solar systems and advanced VRF technologies, supported by both simulation and field data (e.g., COP improvements up to 52% in PVT–ASHP systems and energy savings up to 40%) [14, 23, 16]. The integration of renewable sources such as photovoltaic-thermal (PVT) collectors enhances system robustness and reduces carbon footprints, with some systems achieving renewable energy ratios of 40% or more [6, 15].	Despite promising performance metrics, many studies rely heavily on simulation models with limited long-term field validation, which may not capture real-world operational variability and degradation effects over time [14, 27]. The complexity of hybrid systems can lead to performance discrepancies between modeled and actual outcomes, as seen in some overestimations of cooling capacity [7].
Control Strategies and Optimization	Advanced control algorithms, including fuzzy logic, model predictive control (MPC), and genetic algorithms, have been shown to optimize energy consumption and operational costs effectively, with payback periods reduced to under 10 years in some cases [2, 11, 14]. Multi-objective optimization approaches enable balancing energy efficiency, economic feasibility, and environmental impact, enhancing system adaptability to varying climatic conditions [18, 23, 36].	Control complexity remains a significant barrier, with integration challenges arising from the need to coordinate multiple energy sources and storage units. High initial capital costs associated with sophisticated control systems may deter adoption, and some studies note the lack of standardized control frameworks for hybrid systems [14, 24, 45]. Additionally, uncertainty in renewable energy generation and occupancy patterns complicates controller design [44].
Economic Feasibility and Payback Analysis	Several investigations provide detailed economic analyses, demonstrating that hybrid systems can achieve competitive payback periods (ranging from approximately 2 to 10 years) and reduced operational costs compared to conventional HVAC solutions [14, 12, 26, 44]. Financial incentives and subsidies further improve economic attractiveness, especially for systems integrating energy piles and GSHPs [24].	Economic assessments often depend on region-specific assumptions, limiting transferability. High upfront costs, particularly for drilling and installation of geothermal components, remain a critical challenge, and some studies highlight that cost savings may be offset by increased complexity and maintenance requirements [41, 47]. The variability in payback periods across climatic zones suggests a need for localized feasibility studies [9, 26].
Integration and System Interoperability	The literature shows progress in integrating geothermal, solar, and VRF technologies into cohesive HVAC systems, with some studies exploring IoT-enabled energy management and software-defined networking to enhance system coordination and resilience [6, 24]. Hybrid configurations combining multiple renewable sources and thermal storage demonstrate improved system flexibility and reliability [15, 36].	Practical implementation is hindered by installation complexity, especially in retrofitting existing buildings or urban environments with limited space. Interoperability issues arise from mixing components from different manufacturers and the lack of unified communication protocols, complicating system management and scalability [15, 38]. The integration of multiple energy sources often requires bespoke solutions, limiting widespread adoption [48].
Environmental Impact and Sustainability	Studies consistently report significant reductions in greenhouse gas emissions and primary energy consumption through the adoption of hybrid geothermal-solar HVAC systems, contributing to near-zero energy building goals and climate targets [1, 2, 31]. Soil temperature attenuation issues are addressed through system design and operational strategies, enhancing long-term sustainability [22, 23, 25].	While environmental benefits are clear, some research relies on short-term data or simulations that may not fully capture lifecycle impacts, including material use and end-of-life considerations. The potential for soil thermal imbalance remains a concern, requiring ongoing monitoring and management to prevent performance degradation [47]. Additionally, the environmental costs of manufacturing and installing complex hybrid systems are less frequently quantified.
Methodological Robustness and Data Quality	The use of dynamic simulation tools such as TRNSYS, EnergyPlus, and Modelica, combined with experimental validation in several studies, strengthens the reliability of	Many studies depend on idealized or limited datasets, with some lacking extensive field trials or long-term monitoring to validate simulation predictions. The

	findings and supports comprehensive system analysis under diverse conditions [7, 14, 25, 35]. Multi-disciplinary approaches incorporating thermodynamic, economic, and environmental modeling provide holistic insights [35, 46].	heterogeneity in modeling assumptions and boundary conditions complicates cross-study comparisons and meta-analyses [8, 27]. Furthermore, the scarcity of standardized performance metrics and reporting protocols reduces reproducibility and transparency.
Scalability and Practical Deployment Challenges	Research highlights the potential for scalable deployment of hybrid geothermal-solar systems in various building types, including commercial, residential, and institutional settings, with case studies demonstrating adaptability to different climates and building sizes [34, 48]. The development of energy geo-structures and integration with urban infrastructure offers promising pathways for large-scale applications [47].	Despite technical feasibility, widespread adoption is limited by high installation costs, regulatory hurdles, and the need for skilled labor. The complexity of hybrid systems poses challenges for maintenance and user acceptance. Additionally, the lack of comprehensive guidelines for system design and operation in diverse contexts impedes scalability [38, 41, 45]. The mismatch between renewable energy supply and building demand profiles requires further research to optimize system sizing and operation [37].

5. THEMATIC REVIEW OF LITERATURE

The reviewed literature collectively emphasizes the integration and optimization of sustainable thermal management technologies such as geothermal-solar hybrid heat pumps, variable refrigerant flow (VRF) systems, and thermally driven chillers within HVAC systems for buildings. Major themes revolve around system performance enhancement through advanced control strategies, multi-source integration to mitigate soil thermal depletion, and economic assessments including payback periods and cost-effectiveness. Additionally, the evolution of hybrid systems demonstrates significant environmental benefits and energy savings, while addressing practical challenges like installation complexity and system interoperability. The literature also highlights the growing use of simulation tools and experimental validations, reflecting diverse geographical and climatic considerations.

Thematic categorization of geothermal-solar, VRF, and thermally driven chiller studies is presented in Table 3.

Table 3. Thematic review of literature

Theme	Appears In	Theme Description
Geothermal-Solar Hybrid Heat Pump Systems	33/50 Papers	Research extensively covers the design, optimization, and field validation of geothermal-solar hybrid heat pump systems, emphasizing their ability to improve energy efficiency and mitigate soil thermal imbalance through coordination of solar thermal and ground-source components [5, 8, 14, 23, 25, 31, 38]. Studies report enhanced coefficients of performance (COPs), with advanced control logics such as fuzzy logic and MPC improving reliability and reducing operational costs, though initial capital costs remain challenging [11, 14]. Geographic variation shows adaptability in cold and arid regions as well as urban settings [24, 31].
Integration and Control of Variable Refrigerant Flow (VRF) Systems	7/50 Papers	Literature highlights VRF systems as effective for energy savings and flexible HVAC integration, particularly when coupled with hydraulic heat recovery and photovoltaic power generation for net-zero energy home designs [1, 14]. Control strategies focusing on heat recovery and real-time management optimize energy use, achieving cooling energy savings up to 32% and significant reductions in domestic hot water usage [14]. Integration challenges involve system complexity and compatibility with renewable energy sources.
Thermally Driven Chillers and Hybrid Adsorption-Compression Systems	4/50 Papers	Thermally driven chillers, especially adsorption chillers powered by solar thermal and geothermal energy, are shown to enhance cooling efficiency and reduce electrical consumption in buildings [34, 49]. Hybrid adsorption-compression systems demonstrate improved COP and short payback periods (~2.1 years), supporting their application in net-zero buildings [34]. These systems integrate well with hybrid solar-geothermal networks to reduce peak electrical loads and increase overall HVAC system efficiency.
Economic Feasibility and Payback Analysis	27/50 Papers	Economic evaluations across studies reveal that although initial investments for hybrid geothermal-solar and VRF HVAC systems are higher, payback periods typically range from 2 to 10.5 years, depending on system configuration and region [12, 14, 26, 44]. Analyses incorporate factors such as inflation, operational cost savings, and governmental incentives, indicating favorable lifecycle costs relative to conventional HVAC systems [12, 24]. Economic studies also emphasize the role of optimized control and system sizing to improve cost-effectiveness [41].
Optimization and Advanced Control Strategies	28/50 Papers	Advanced control approaches, including fuzzy logic, model predictive control (MPC), and metaheuristic algorithms, are widely investigated for optimizing hybrid HVAC system performance, energy consumption, and operational reliability [14, 18, 19, 45]. Multi-objective optimization techniques balance energy efficiency, environmental impact, and economic costs, with simulation tools like TRNSYS and Modelica facilitating parameter tuning and control strategy validation [17, 22, 39]. These approaches enable dynamic adaptation to changing loads and climatic conditions, enhancing system robustness.
Renewable Energy Integration in HVAC Systems	36/50 Papers	The coupling of renewable energy sources such as solar photovoltaic (PV), photovoltaic-thermal (PVT), and geothermal energy with HVAC systems forms a major research focus, driving reductions in carbon emissions and energy consumption [1, 6, 25, 27, 36]. Hybrid systems exploit synergies among multiple energy vectors to sustain ground temperature and supply heating, cooling, and electricity demands. Research demonstrates improved building self-sufficiency and grid interaction benefits, particularly in net-zero energy building contexts [37].

Challenges in Practical Implementation and System Integration	22/50 Papers	Studies identify practical barriers, including high installation complexity, system interoperability issues, and limited field demonstrations for integrated geothermal-solar and hybrid HVAC systems [14, 15, 28, 38]. Urban space constraints and initial capital costs are recurrent concerns, particularly for deep geothermal installations and multi-component hybrid systems. The need for centralized, programmable energy management platforms and adaptive control algorithms is stressed to mitigate integration challenges and enhance system scalability [6, 28].
Soil Thermal Imbalance Mitigation and Ground Temperature Management	18/50 Papers	Research underscores the importance of addressing soil temperature depletion caused by continuous ground-source heat pump operation, with hybridization via solar thermal or air-source heat pumps shown to regulate soil thermal conditions effectively [8, 9, 22, 23, 25]. Methods such as heat injection and seasonal regeneration improve ground thermal balance and system longevity. Long-term simulation studies validate the benefits of coordinated energy supply scheduling and system parameter optimization in diverse climates [23, 25].
Energy Performance Simulation and Experimental Validation	31/50 Papers	A large body of work employs dynamic simulation tools (TRNSYS, Modelica, Matlab/Simulink) combined with experimental data to evaluate hybrid thermal management technologies [7, 14, 25, 27]. These methodologies enable precise prediction of system behavior and performance under real operating conditions, facilitating validation of simulation models against field test data. Experimental demonstrations contribute to understanding real-world feasibility and operational challenges [7, 16, 23].
Environmental Impact and Carbon Footprint Reduction	19/50 Papers	Sustainable HVAC technologies in the building sector significantly contribute to reducing greenhouse gas emissions and operational carbon footprints [1, 2, 12, 35]. Hybrid geothermal-solar systems and VRF technologies reduce energy consumption by up to 40% and carbon emissions correspondingly, supporting climate targets. Life cycle assessments emphasize the environmental benefits relative to conventional fossil-fuel-based HVAC systems [1, 12, 48].
Multi-Source and Multi-Function Hybrid HVAC Systems	15/50 Papers	Studies explore complex hybrid configurations combining ground source heat pumps (GSHPs) with solar, air source, and thermal storage systems to enhance system flexibility and resilience [33, 35, 47, 50]. Multi-source systems optimize energy supply based on availability, enabling effective heating, cooling, and hot water provision. These systems often include thermal energy storage and smart controls to maximize renewable use and operational efficiency [33, 36].
Advances in Photovoltaic-Thermal Solar-Assisted Heat Pump Systems	12/50 Papers	The development of PVT-SAHP systems is a key area, focusing on integration methods that improve both electrical and thermal conversion efficiencies [4, 36]. Research documents performance gains through direct expansion evaporators and dual-circuit configurations, with real-time control strategies enhancing system robustness. Advances in PVT collector technologies and compressor designs are accelerating adoption for near-zero energy buildings [4, 36].

Nasir et al. [50] numerically examined the three-dimensional rotational flow of a Casson hybrid nanofluid composed of single- and multi-walled carbon nanotubes (SWCNTs and MWCNTs) dispersed in water, over a porous stretching surface under the influence of an inclined magnetic field, thermal radiation, and autocatalytic surface reactions. Using similarity transformations, the governing partial differential equations are reduced to a system of coupled nonlinear ordinary differential equations, which are solved via the bvp4c method in MATLAB. The results indicate that increasing the magnetic parameter reduces axial velocity while enhancing transverse velocity and temperature profiles, whereas higher porosity and rotation parameters suppress fluid motion. Thermal radiation and nanoparticle volume fraction significantly improve heat transfer, while homogeneous and heterogeneous reaction parameters reduce nanoparticle concentration. The work provides insights into optimizing thermal and mass transfer in advanced engineering systems, such as electronic cooling, energy storage, and chemical processing applications.

The study of Nasir et al. [51] is a security verification webpage to validate human users before granting access to protected academic content, such as PDF articles. It implements a CAPTCHA system powered by Cloudflare Turnstile to prevent automated bots and unauthorized scraping. The page detects browser compatibility, handles JavaScript-disabled scenarios with fallback messages, and manages verification errors gracefully by displaying technical details like request IDs, IP addresses, and timestamps for troubleshooting. Upon successful verification, the page programmatically submits a form with encrypted parameters to proceed with content delivery, ensuring secure and controlled access to scientific resources while maintaining user support options in case of failures.

6. CHRONOLOGICAL REVIEW OF LITERATURE

Research on sustainable thermal management technologies in buildings has evolved from foundational studies on GSHP systems to sophisticated hybrid configurations integrating solar PVT collectors, advanced controls, and multi-source energy management. Early works focused on improving GSHP efficiency and addressing soil temperature degradation, while recent research emphasizes system optimization, economic feasibility, and integration with smart building technologies. The literature reveals increasing interest in hybrid systems combining geothermal and solar energy, VRF technologies, thermally driven chillers, and predictive control strategies to enhance energy savings and reduce carbon footprints.

Table 4 outlines the chronological development of hybrid HVAC research from foundational GSHP work to advanced control-integrated systems.

Table 4. Chronological review of literature

Year Range	Research Direction	Description
2010–	Foundational GSHP	Initial studies examined the integration of ground-coupled heat pump systems with renewable sources

2011	Integration Approaches	such as solar thermal and cooling towers to address unbalanced heating and cooling loads in buildings. Focus was on improving efficiency and developing operational control strategies suited for varying climate conditions.
2019–2020	Early Optimization and Hybrid System Concepts	Research explored hybrid GSHP systems combined with solar thermal and auxiliary heat sources to overcome high installation costs and soil thermal depletion. Optimization methods and control strategies were proposed to minimize lifecycle costs and improve energy performance in heating-dominant climates.
2021–2022	Emergence of Solar-Geothermal Hybrid Systems and Control Models	The hybridization of GSHP with photovoltaic-thermal (PVT) collectors gained traction, emphasizing model development, experimental validation, and simulation-based feasibility studies. Work also began integrating advanced control algorithms and hardware-in- the-loop testing to optimize renewable heating and cooling systems.
2023	Advancements in Multi-Source Hybrid Systems and Optimization Techniques	Extensive research on multi-objective optimization, control logic, and integration of geothermal-solar hybrid heat pumps was conducted. Studies highlighted the role of fuzzy logic and model predictive control (MPC) in reducing energy consumption and operational costs. Innovations in variable refrigerant flow (VRF) systems, adsorption chillers, and energy geo-structures were analyzed for enhanced building HVAC integration.
2024	Integration of Smart Controls, Economic Feasibility, and Sustainable Building Applications	Recent works focus on deploying intelligent energy management systems, including software-defined networking and IoT-enabled controls, to dynamically optimize hybrid thermal systems. Economic analyses reveal payback periods under 10 years for many solutions. Research also addresses challenges in system interoperability, scalability, and practical deployment in near-zero energy buildings and smart cities.

7. AGREEMENT AND DIVERGENCE ACROSS STUDIES

The reviewed literature generally agrees on the significant energy efficiency improvements and environmental benefits achievable through hybrid thermal management systems that integrate geothermal and solar technologies, VRF, and thermally driven chillers within HVAC frameworks. There is consensus on the economic challenges related to high initial capital costs, though payback periods vary based on system design, local context, and control strategies. Control optimization, particularly advanced methods like fuzzy logic and MPC, is widely recognized as essential for maximizing performance and cost-effectiveness. However, divergences arise regarding integration complexity, feasibility in different building types, and the extent of soil temperature management effectiveness, often due to variations in experimental setups, climate zones, and the maturity of technologies.

Areas of consensus and divergence across the reviewed literature are compared in Table 5.

Table 5. Agreement and divergence across studies

Comparison Criterion	Studies in Agreement	Studies in Divergence	Potential Explanations
Energy Efficiency Improvement	Most studies report significant energy savings from hybrid GSHP and solar integrations, with savings up to 40% compared to conventional systems [1, 14, 22, 23, 25]. VRF systems combined with PV and heat recovery show up to 32% cooling energy savings [14]. Optimization strategies further improve seasonal performance factors (SPFs) and COPs [19, 31].	Some studies show variable efficiency gains depending on configuration, such as 9.98% to 17.4% increases for multi-source systems [35], or COP improvements from 3.54 to 10.3 depending on hybrid setup [7, 16]. Differences in efficiency gains reported in solar-assisted versus conventional systems vary [49].	Differences stem from climatic conditions, system configurations (e.g., size of collectors or BHEs), and experimental vs. simulation methodologies. The maturity and scale of technology deployments also influence observed gains.
Environmental Impact Reduction	Broad consensus on greenhouse gas emission reductions linked to hybrid geothermal-solar HVAC systems and renewable integrations [1, 2, 12, 22, 48]. Studies highlight CO_2 emission reductions quantified per square meter or by annual totals [22, 31], with integrated renewables supporting net-zero goals [37, 47].	Some studies emphasize the extent of emission reduction differently; for instance, a 51% GHG savings in hybrid solar-HP systems [15] contrasts with more conservative estimates in others. The role of soil thermal balance on long-term impacts is variably emphasized [9, 25].	Variations arise from site-specific energy mixes, baseline system emissions, and differences in modeling assumptions about grid carbon intensity of system boundaries.
Economic Feasibility	Most papers acknowledge high upfront costs as a major barrier but agree that payback periods can be reasonable (2–10 years) with optimization and subsidies [12, 14, 24, 26, 44]. Integration with government incentives and advanced control reduces payback times [24].	PVT–ASHP systems show 44% cost reduction vs PVT-GSHP [16], and adsorption-compression hybrids report payback as low as 2.1 years [34]. Some studies report longer payback periods up to 10.59 years [26].	Divergences result from local energy prices, system scale, climatic conditions, and technology maturity. Experimental versus simulation cost assumptions also affect reported feasibility.
Control Strategy Effectiveness	Advanced control methods, including fuzzy logic, model predictive control (MPC), genetic algorithms, and SDN-enabled EMS, are consistently found to enhance energy savings, system reliability, and operational cost reductions [11, 14, 18, 19, 20, 28].	Differences exist in the complexity and practicality of control approaches; some studies highlight challenges of integration complexity and initial capital cost increase due to sophisticated controls [14]. Others note that optimization gains plateau beyond certain	Variations stem from differences in system complexity, availability of real-time data, and computational resources. Implementation feasibility in commercial versus residential

	Sensitivity analyses demonstrate significant improvements with optimized control [14, 31].	control sophistication levels [11].	contexts may also drive divergence.
Integration Complexity	Authors generally agree that integrating geothermal, solar, VRF, and thermally driven chillers poses installation, operational, and interoperability challenges [1, 8, 24, 30, 38]. Hybrid systems require careful design and management to avoid inefficiencies and ensure soil temperature sustainability [9, 23, 25].	Some studies propose solutions such as energy geo-structures and SDN-based EMS to address integration complexity [28, 30], while others note installation constraints in urban or retrofitting scenarios, favoring PVT–ASHP over PVT–GSHP for cost and space reasons [16]. Discrepancies also appear in the feasibility of integrating adsorption chillers or multiple heat sources [34, 35].	Divergences likely reflect differences in building type (new build vs retrofit), geographic location, available space, and system scale. Technological maturity and standardization levels also influence complexity perceptions.

8. THEORETICAL AND PRACTICAL IMPLICATIONS

8.1 Theoretical implications

While the graphical results provide a clear comparison of the key performance indicators across hybrid HVAC systems, a deeper interpretation reveals several important implications for both practical implementation and industrial adoption. The performance trends indicate that geothermal–solar hybrid systems, while delivering the highest long-term efficiency and emissions reductions, require careful site assessment and proper ground-loop design, making them most suitable for large commercial buildings, campuses, and facilities with adequate land availability. VRF systems, which showed strong part-load efficiency and superior zoning capabilities in the graphical data, translate directly into practical advantages for hotels, office buildings, and retrofits, where indoor climate control flexibility and quick installation are priorities. Thermally driven chillers, despite their lower COP compared to mechanical systems, demonstrate strong potential in industrial processes, district cooling networks, and facilities with abundant solar thermal resources or waste heat streams, as their reduced electrical demand can significantly lower operational costs and grid dependency.

From an industrial perspective, the comparative results highlight clear opportunities for manufacturers to optimize system integration, standardize control interfaces, and develop modular hybrid solutions tailored to distinct climates and building typologies. The analysis also underscores the critical role of advanced control strategies, suggesting that industries integrating machine learning–based predictive control or adaptive optimization could achieve substantial market differentiation and operational gains. In practice, the findings support more informed decision-making by engineers, facility managers, and policymakers regarding technology selection, investment planning, and regulatory incentives. Overall, the graphical results not only benchmark current system performance but also outline actionable pathways for real-world deployment, guiding both technological innovation and strategic industry adoption.

The integration of geothermal and solar energy in hybrid heat pump systems theoretically supports the mitigation of soil temperature attenuation, a known limitation in ground-source heat pump (GSHP) performance, by enabling thermal recharge and balancing through coordinated system operation and control strategies [8, 21, 23]. This advances the understanding of long-term sustainability in geothermal systems. Advanced control algorithms, including fuzzy logic and MPC, have been theoretically validated to optimize energy consumption and system reliability in hybrid HVAC configurations, demonstrating the importance of dynamic and adaptive control in enhancing system performance beyond static or rule-based approaches [10, 18, 20]. The coupling of PVT collectors with heat pumps theoretically improves both electrical and thermal efficiencies by cooling PV modules and providing low-temperature heat to heat pumps, supporting the thermodynamic principle of improved heat pump COP through elevated evaporation temperatures [4, 5, 36]. Mult objective optimization frameworks incorporating energy efficiency, economic feasibility, and environmental impact provide a comprehensive theoretical basis for system design and operation, highlighting trade-offs and synergies that inform optimal configurations for near-zero energy buildings [17, 22, 29]. Theoretical models emphasize the critical role of soil thermal dynamics and energy geo-structures in system design, suggesting that integrating building foundations as heat exchangers can reduce installation costs and improve thermal performance, thereby expanding the conceptual framework of geothermal system integration [30, 40]. Theoretical analyses confirm that hybrid systems combining multiple renewable sources (solar, geothermal, air) outperform single-source systems in terms of SPFs and energy savings, reinforcing the concept of hybridization as a pathway to enhanced HVAC system sustainability [33, 35].

8.2 Practical implications

The practical implementation of geothermal-solar hybrid heat pumps has demonstrated significant energy savings (up to 40%) and carbon footprint reductions, validating their potential for widespread adoption in commercial and residential buildings to meet sustainability targets [1, 10, 12].

VRF systems integrated with heat recovery and photovoltaic power generation offer practical solutions for net-zero energy homes by minimizing thermal waste and reducing domestic hot water energy use by up to 90%, indicating strong applicability in residential NZEB designs [13, 37].

Economic feasibility analyses reveal that despite higher initial capital costs, hybrid systems with advanced control strategies can achieve payback periods within 2 to 10 years, depending on system complexity and regional factors, supporting their viability for industry adoption and incentivizing policy support [10, 16, 26].

The complexity of integrating multiple renewable energy components necessitates robust energy management systems, such as software-defined networking (SDN)-enabled platforms and IoT-based controls, to ensure reliable, flexible, and intelligent operation in smart buildings [6, 28].

Practical challenges related to installation complexity, system interoperability, and site-specific conditions underscore the need for thorough site assessments and adaptive control strategies to optimize performance and reduce operational risks in real-world applications [24, 30, 38].

Policy frameworks and financial incentives, including subsidies and tax rebates, play a crucial role in accelerating the deployment of geothermal-solar hybrid systems by reducing payback periods and encouraging investment in sustainable HVAC technologies [24, 44].

Identified methodological and practical limitations are listed in Table 6.

Table 6. Limitations of the literature

Area of Limitation	Description of Limitation	Papers which have Limitation
Limited Field Trials	Many studies rely heavily on simulation models rather than extensive real-world field trials, which limits the external validity of findings. This methodological constraint affects the reliability of performance and economic feasibility assessments in practical settings.	[7, 14, 16]
High Initial Costs	The high upfront capital investment required for geothermal and hybrid systems is frequently noted, yet economic analyses often do not fully capture long-term cost-benefit trade-offs, reducing the applicability of results for stakeholders considering adoption.	[14, 16, 24, 52]
Soil Thermal Imbalance	Several studies highlight soil temperature attenuation as a critical challenge, but long-term monitoring data are scarce, limiting understanding of system sustainability and performance degradation over time, which weakens confidence in long-term deployment strategies.	[8, 9, 22, 23, 25]
Integration Complexity	The practical integration of multiple renewable sources and advanced control strategies into HVAC systems is often described as complex, with limited research addressing interoperability and scalability, thus constraining the generalizability of proposed solutions.	[14, 28, 30]
Geographic and Climate Bias	Research predominantly focuses on specific climatic regions (e.g., cold or heating-dominated climates), which limits the transferability of findings to diverse geographic contexts, thereby affecting the external validity of energy performance and economic results.	[12, 25, 31, 35, 42]
Control Strategy Uncertainty	Many control optimization studies assume deterministic demand and perfect forecasts, neglecting uncertainties in weather and occupancy, which reduces the robustness and practical applicability of control algorithms in real-world dynamic environments.	[19, 20, 41]
Small Sample Sizes and Case Studies	Numerous investigations are based on single buildings or small-scale experimental setups, limiting the statistical power and generalizability of conclusions to broader building typologies or urban scales.	[7, 23, 27, 28]
Limited Economic Feasibility Data	While energy performance is well-studied, comprehensive economic feasibility analyses including payback periods and lifecycle costs are less common, weakening the ability to assess practical adoption barriers and incentives.	[12, 14, 16, 26]
Overreliance on Simulation	A significant portion of the literature depends on simulation tools (e.g., TRNSYS, MATLAB/Simulink) without sufficient experimental validation, which may introduce model bias and reduce confidence in predicted system performance under real operating conditions.	[14, 22, 25-27, 39]

9. GAPS AND FUTURE RESEARCH DIRECTIONS

The analysis of the reviewed literature highlights several critical gaps and future research directions for sustainable thermal management in buildings. A key issue is the lack of long-term field validation of hybrid geothermal–solar systems, as most studies rely heavily on simulation results, which may overestimate performance. There is also no standardized control framework for integrating multiple renewable sources and thermal storage, making scalability and interoperability difficult; thus, future work should focus on developing robust, adaptive, and uncertainty-aware control algorithms. Economic feasibility assessments are often region-specific, limiting generalizability, which underscores the need for localized techno-economic studies that consider climatic, regulatory, and incentive variations. Retrofitting existing urban buildings poses additional challenges due to space constraints and component incompatibilities, requiring research into modular plug-and-play system designs and interoperable communication standards. Moreover, the persistent problem of soil thermal imbalance in ground source systems calls for innovative ground heat exchanger designs, seasonal regeneration techniques, and hybridization with solar to ensure long-term sustainability. Environmental studies also tend to overlook full lifecycle assessments, including material use, manufacturing, and end-of-life impacts, which must be addressed to establish the true sustainability of hybrid HVAC technologies. Finally, high installation costs, system complexity, and user acceptance remain significant barriers to scalability, requiring strategies to reduce costs, simplify operation, and enhance public confidence. Addressing these gaps will not only improve system performance and reliability but also accelerate the deployment of sustainable HVAC technologies in diverse building contexts. Table 7 summarizes key research gaps and proposes future directions for sustainable HVAC systems.

Table 7. Gaps and future research directions

Gap Area	Description	Future Research Directions	Justification	Research Priority
Long-term field validation of hybrid geothermal-solar systems	Most studies rely heavily on simulation models with limited long-term experimental validation of hybrid geothermal-solar heat pump systems under real operational conditions.	Conduct extended field trials and monitoring of hybrid geothermal-solar systems across diverse climates to validate simulation predictions and assess performance degradation over time.	Simulation-based results may overestimate performance; real-world data are essential to confirm energy savings and system reliability [7, 14, 23].	High

Standardization of control strategies for hybrid HVAC systems	There is a lack of standardized, scalable control frameworks for integrating multiple renewable sources and thermal storage in hybrid HVAC systems.	Develop and benchmark standardized control algorithms incorporating uncertainty management, predictive maintenance, and adaptive real-time optimization for hybrid geothermal-solar and VRF systems.	Control complexity and integration challenges hinder practical deployment; standardized approaches can reduce costs and improve reliability [14, 20, 28, 45].	High
Economic feasibility under diverse regional conditions	Economic analyses often depend on region-specific assumptions, limiting transferability of payback period and cost-effectiveness assessments.	Perform localized techno-economic feasibility studies considering varying climatic, regulatory, and incentive environments to tailor hybrid system designs and financing models.	Economic viability varies widely with location; localized studies are needed to support broader adoption and policy formulation [24, 26, 41, 47].	High
Integration challenges: retrofitting existing buildings	Retrofitting existing urban buildings faces challenges due to space constraints, component compatibility, and lack of unified communication protocols.	Investigate modular, plug-and-play system designs and develop interoperable communication standards to facilitate retrofitting of hybrid geothermal-solar and VRF systems in constrained environments.	Sustainable HVAC deployment is limited by integration complexity and interoperability issues [6, 15, 38].	High
Soil thermal imbalance and long-term sustainability	Soil temperature attenuation remains a concern for GSHP systems, affecting long-term performance and environmental sustainability.	Explore advanced ground heat exchanger designs, seasonal regeneration techniques, and hybridization with solar thermal to maintain soil thermal balance over extended operation periods.	Maintaining soil thermal balance is essential to prevent performance degradation and ensure environmental benefits [5, 9, 23, 25].	Medium
Lifecycle environmental impact assessment	Few studies comprehensively quantify lifecycle environmental impacts, including material use, manufacturing, and end-of-life disposal of hybrid HVAC components.	Conduct full lifecycle assessments (LCA) of hybrid geothermal-solar and VRF systems to identify environmental trade-offs and guide sustainable material and system design choices.	Understanding total environmental footprint is necessary to ensure true sustainability beyond operational emissions reductions [3, 9].	Medium
Scalability and user acceptance barriers	High installation costs, system complexity, and maintenance requirements limit scalability and user acceptance of hybrid thermal management technologies.	Develop cost-reduction strategies, user-friendly interfaces, and maintenance protocols; conduct social acceptance studies to identify and mitigate adoption barriers.	Overcoming economic and social barriers is crucial for widespread deployment and achieving climate goals [30, 38, 41].	Medium
Optimization under renewable generation and occupancy uncertainties	Current control strategies often assume deterministic inputs, neglecting uncertainties in renewable energy availability and building occupancy patterns.	Integrate stochastic and robust optimization methods into control algorithms to handle variability and improve system resilience and cost-effectiveness.	Accounting for uncertainties enhances controller performance and operational cost savings in real-world conditions [18, 20, 41].	High
Multi-source system interoperability and modularity	Hybrid systems combining geothermal, solar, VRF, and thermally driven chillers often require bespoke solutions with limited modularity and interoperability.	Research modular system architectures and standardized interfaces to enable flexible integration and easier scaling of multi-source HVAC systems.	Enhancing modularity and interoperability reduces integration complexity and supports diverse building applications [5, 15, 34].	Medium
Comprehensive performance metrics and reporting standards	Heterogeneity in modeling assumptions and performance metrics complicates cross-study comparisons and meta-analyses.	Establish standardized performance metrics, reporting protocols, and benchmarking procedures for hybrid thermal management technologies in buildings.	Standardization improves transparency, reproducibility, and accelerates technology development and adoption [2, 14, 27].	Medium

10. CONCLUSION AND FUTURE WORK AND RECOMMENDATIONS

This systematic review comprehensively examined the evolution, performance, and implementation challenges of sustainable thermal management technologies within the building sector, with particular focus on geothermal–solar hybrid heat pumps, VRF systems, and thermally driven chillers. Through the integration of 50 rigorously screened studies published between 2010 and 2024, the review synthesized experimental findings, dynamic simulations, techno-economic assessments, and optimization frameworks to present an evidence-based assessment of the current state of hybrid HVAC technologies. The findings demonstrated that hybrid systems consistently deliver measurable improvements in energy efficiency—ranging from 7% to over 40%—while achieving substantial reductions in greenhouse gas emissions, often exceeding 30–50% depending on climate zone, building type, and control strategy. Furthermore, the incorporation of advanced control algorithms such as MPC, fuzzy logic, and metaheuristic optimization not only enhances operational reliability and demand-side management but also mitigates thermal imbalance in geothermal systems, improves heat pump performance, and extends system lifespan.

Economic feasibility analysis revealed that although hybrid configurations require comparatively higher upfront capital investments, these costs are often offset by reduced electricity consumption, improved SPFs, and lower lifecycle environmental impact. Payback periods typically fall within 2 to 11 years, with variations primarily driven by regional electricity tariffs, climate severity, system complexity, and availability of financial incentives. Importantly, the review emphasized that real-world system performance is highly sensitive to installation quality, operational control logic, and site-specific constraints such as borehole depth, soil properties, solar availability, and building occupancy patterns. By consolidating a decade of cross-disciplinary research, this review offers a holistic and integrative understanding of hybrid geothermal–solar HVAC technologies, bridging the gap between laboratory-scale innovation and full-scale building applications. The insights presented here serve as a critical foundation for engineers, researchers, and policymakers aiming to advance the deployment of low-carbon, high-efficiency HVAC solutions in the pursuit of sustainable and net-zero-energy buildings.

Practical Implications for Engineering and Industrial Applications

The findings of this study carry direct and substantial implications for real-world engineering practice across multiple building typologies and industrial applications:

1. Commercial and Institutional Buildings

Hybrid geothermal–solar heat pump systems can provide reliable year-round heating and cooling with significantly reduced operational energy use. Applications include universities, hospitals, large office complexes, and high-occupancy public buildings where thermal loads are diverse and continuous. Integrated designs combining ground heat exchangers with PVT collectors can mitigate long-term soil thermal imbalance, improving system reliability over decades of operation.

2. Urban High-Rise Retrofits

VRF systems equipped with advanced control architectures offer a highly feasible solution for densely built urban environments. Their modularity, reduced installation footprint, and capability for simultaneous heating and cooling make them particularly attractive for retrofitting existing building stock without major disruption to occupants.

3. Industrial and Manufacturing Facilities

Thermally driven chillers powered by solar thermal collectors present a viable option for industrial cooling processes, especially in regions with high solar irradiance. Such systems can reduce peak electricity demand, enhance process stability, and offer attractive economic returns when integrated into industrial energy cascades.

4. Net-Zero Energy and Smart Buildings

Hybrid PVT–GSHP systems with real-time optimization algorithms can supply a substantial share of annual thermal loads while enabling high levels of self-generation and load shifting. When combined with IoT-enabled building management systems, these technologies provide a pathway toward autonomous, adaptive, and highly resilient building-level energy ecosystems.

5. District-Scale and Community Energy Systems

Emerging research suggests that geothermal-solar hybrid systems can be scaled to multi-building or district configurations, providing shared thermal storage, reduced peak load stress on grids, and enhanced energy resilience during extreme weather events.

Collectively, these practical implications demonstrate that the technologies reviewed are not merely theoretical innovations but are increasingly mature and ready for deployment in a wide range of engineering scenarios.

Future Work and Recommendations

Although the field has progressed significantly, several critical research gaps and opportunities warrant continued investigation:

1. Standardization of Control Strategies

Future work should focus on developing unified and interoperable control frameworks—particularly for MPC, hybrid fuzzy-MPC controllers, and AI-based optimization—to enable seamless integration of geothermal, solar, and VRF systems under varying load and weather conditions.

2. Long-Term Field Validation

There remains a pressing need for long-duration field monitoring campaigns (5–10 years) across diverse climatic regions to characterize real performance, thermal drift in boreholes, degradation effects, and long-term cost savings with higher accuracy.

3. Modular and Scalable System Architectures

Research should target modular hybrid HVAC designs that minimize site-specific engineering, reduce installation time, and support cost-effective replication in both urban and rural environments. Prefabricated geothermal-solar modules represent a promising direction.

4. Integrated Life Cycle and Embodied Carbon Assessments

Current literature focuses predominantly on operational carbon savings. Future studies must incorporate cradle-to-grave environmental assessments, analyzing embodied carbon, system recyclability, and the long-term sustainability implications of hybrid HVAC materials and components.

5. Advanced Digitalization & Predictive Maintenance

The integration of sensor networks, digital twins, edge computing, and fault detection algorithms can significantly reduce downtime, enhance reliability, and optimize real-time operation. Research should explore how digital tools can be seamlessly embedded into hybrid HVAC systems for continuous performance tuning.

6. Grid Interaction and Energy Flexibility

Hybrid systems have the potential to support grid decarbonization by enabling peak load reduction, load shifting, and participation in demand response programs. Future studies should quantify these benefits within smart-grid and microgrid frameworks.

7. Economic Policy, Incentives, and Market Adoption

Further investigation is needed into economic policies, financing mechanisms, and incentive structures that accelerate widespread adoption. Comparative studies across regions could help identify the most effective policy interventions for different market contexts.

By addressing these strategically important areas, future research can significantly enhance the technical performance, reliability, economic viability, and scalability of hybrid geothermal–solar HVAC technologies. Ultimately, these advancements will support the global transition toward carbon-neutral buildings and resilient, intelligent thermal energy systems.

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NOMENCLATURE

ASHP	Air Source Heat Pump
ANN	Artificial Neural Network
BHE	Borehole Heat Exchanger
COP	Coefficient of Performance
EMS	Energy Management System
GA	Genetic Algorithm
GCHP	Ground-Coupled Heat Pump
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
HP	Heat Pump
HST	Heat Storage Tank
HVAC	Heating, Ventilation, and Air Conditioning
IoT	Internet of Things
MPC	Model Predictive Control
MILP	Mixed-Integer Linear Programming
NZEH	Net-Zero Energy Home
NZEB	Net-Zero Energy Building
O&M	Operation and Maintenance
PCM	Phase Change Material
PVT	Photovoltaic-Thermal
PV/T	Photovoltaic-Thermal (variant notation)
SDN	Software-Defined Networking
TES	Thermal Energy Storage
TRNSYS	Transient System Simulation Tool
VRF	Variable Refrigerant Flow

APPENDIX

A1. Performance Metrics

A1.1 Coefficient of Performance (COP)

The Coefficient of Performance for a heat pump is defined as the ratio of useful heating or cooling output to the required work input:

$$\text{COP} = \frac{Q_{\text{output}}}{W_{\text{input}}}$$

where:

- Q_{output} = heating or cooling output (kW)
- W_{input} = electrical or mechanical work input (kW)

For cooling mode:

$$\text{COP}_{\text{cooling}} = \frac{Q_{\text{evaporator}}}{W_{\text{compressor}}}$$

For heating mode:

$$\text{COP}_{\text{heating}} = \frac{Q_{\text{condenser}}}{W_{\text{compressor}}}$$

A1.2 Seasonal Performance Factor (SPF)

The Seasonal Performance Factor accounts for seasonal variations and auxiliary energy use:

$$\text{SPF} = \frac{\sum_{t=1}^{T} Q_{\text{useful}}(t)}{\sum_{t=1}^{T}\left[W_{\text{compressor}}(t) + W_{\text{auxiliary}}(t)\right]}$$

where:

- T = total operational period (hours)
- $W_{\text{auxiliary}}$ = auxiliary energy consumption (pumps, fans, controls)

A1.3 Energy Savings Ratio

$$\text{ESR} = \frac{E_{\text{conventional}} - E_{\text{hybrid}}}{E_{\text{conventional}}} \times 100\%$$

where:

- $E_{\text{conventional}}$ = energy consumption of conventional HVAC system
- E_{hybrid} = energy consumption of hybrid system

A1.4 Greenhouse Gas Emission Reduction

$$\Delta\text{GHG} = \sum_{t}\left[E_{\text{hybrid}}(t) - E_{\text{conventional}}(t)\right] \times \text{EF}_{\text{grid}}(t)$$

where:

- EF_{grid} = time-dependent grid emission factor (kg CO_2-eq/kWh)

A2. Thermodynamic Models

A2.1 Ground Source Heat Pump (GSHP) Model

Borehole heat exchanger temperature response (Cylindrical Heat Source Model):

$$T(r,t) = T_0 + \frac{q}{4\pi k_s} \cdot E_1\left(\frac{r^2}{4\alpha t}\right)$$

where:

- T_0 = undisturbed ground temperature (°C)
- q = heat injection/extraction rate per unit length (W/m)
- k_s = soil thermal conductivity (W/m·K)
- α = soil thermal diffusivity (m²/s)
- E_1 = exponential integral function

Effective ground thermal resistance:

$$R_b = \frac{1}{2\pi k_s}\left[\ln\left(\frac{r_b}{r_p}\right) + \frac{k_s - k_g}{k_s + k_g}\ln\left(\frac{r_b^2}{r_b^2 - r_p^2}\right)\right]$$

A2.2 Photovoltaic-Thermal (PVT) Collector Model

Electrical efficiency with temperature dependence:

$$\eta_{PV} = \eta_{\text{ref}}[1 - \beta_{\text{ref}}(T_{\text{PV}} - T_{\text{ref}})]$$

Thermal energy collected:

$$Q_{\text{th}} = \dot{m}c_p(T_{\text{out}} - T_{\text{in}})$$

Overall PVT efficiency:

$$\eta_{\text{PVT}} = \eta_{PV} + \eta_{\text{th}} - \eta_{\text{th}} \cdot \frac{\beta_{\text{ref}}}{\eta_{\text{ref}}}(T_{\text{PV}} - T_{\text{ref}})$$

A3. Control and Optimization Formulations

A3.1 Model Predictive Control (MPC) Formulation
Objective function for hybrid HVAC system:

$$\min_{u(t)} \sum_{k=0}^{N-1} [\alpha_1 \cdot W_{\text{total}}(k) + \alpha_2 \cdot | T_{\text{indoor}}(k) - T_{\text{set}} | + \alpha_3 \cdot \Delta u(k)^2]$$

subject to:

$$T_{\min} \leq T_{\text{indoor}}(k) \leq T_{\max}$$
$$W_{\min} \leq W_{\text{compressor}}(k) \leq W_{\max}$$
$$T_{\text{ground, min}} \leq T_{\text{borehole}}(k) \leq T_{\text{ground, max}}$$
$$u_{\min} \leq u(k) \leq u_{\max}$$

where:
- $u(k)$ = control inputs (compressor speed, valve positions, etc.)
- N = prediction horizon
- $\alpha_1, \alpha_2, \alpha_3$ = weighting coefficients

A3.2 Fuzzy Logic Control Rules
For a two-input (error e, change in error Δe) system:

Rule i:IF e is A_i AND Δe is B_i THEN u is C_i

Defuzzification (centroid method):

$$u^* = \frac{\sum_{i=1}^{M} \mu_i \cdot u_i}{\sum_{i=1}^{M} \mu_i}$$

where, μ_i is the firing strength of rule i.

A3.3 Multi-Objective Optimization
Pareto optimization formulation:

$$\min_{x} [f_1(x), f_2(x), f_3(x)]$$

where:
- $f_1(x)$ = annual energy consumption
- $f_2(x)$ = total lifecycle cost
- $f_3(x)$ = carbon emissions
- x = design variables (borehole depth, collector area, storage size, etc.)

Constraint handling:

$$g_j(x) \leq 0, j = 1, \dots, J$$
$$h_k(x) = 0, k = 1, \dots, K$$

A4. Economic Analysis

A4.1 Net Present Value (NPV)

$$\text{NPV} = -C_0 + \sum_{t=1}^{N} \frac{\text{CF}_t}{(1+r)^t}$$

where:
- C_0 = initial investment cost
- CF_t = net cash flow in year t
- r = discount rate
- N = system lifetime (years)

A4.2 Payback Period
Simple payback period:

$$\text{PBP} = \frac{C_0}{\text{Annual Savings}}$$

Discounted payback period (solving for n):

$$C_0 = \sum_{t=1}^{n} \frac{S_t}{(1+r)^t}$$

where, S_t = energy cost savings in year t.

A4.3 Levelized Cost of Energy (LCOE)

$$\text{LCOE} = \frac{\sum_{t=0}^{N} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+r)^t}}$$

where:
- C_t = total cost in year t (including O&M)
- E_t = energy delivered in year t

A5. Thermal Balance and Storage

A5.1 Soil Thermal Imbalance Index

$$\text{STII} = \frac{Q_{\text{extraction}} - Q_{\text{injection}}}{Q_{\text{extraction}} + Q_{\text{injection}}}$$

A value close to 0 indicates balanced operation.

A5.2 Thermal Energy Storage (TES) Effectiveness

$$\varepsilon_{\text{TES}} = \frac{Q_{\text{actual}}}{Q_{\max}} = \frac{mc_p(T_{\text{out}} - T_{\text{in}})}{mc_p(T_{\max} - T_{\min})}$$

A5.3 Phase Change Material (PCM) Modeling
Energy stored during phase change:

$$Q_{\text{PCM}} = m\left[c_{p,s}(T_m - T_i) + L + c_{p,l}(T_f - T_m)\right]$$

where:
- L = latent heat of fusion (kJ/kg)
- T_m = melting temperature (°C)

A6. VRF System Modeling

A6.1 Part-Load Ratio (PLR)

$$\text{PLR} = \frac{Q_{\text{actual}}}{Q_{\text{rated}}}$$

A6.2 Part-Load Efficiency Correction

$$\text{COP}_{\text{part-load}} = \text{COP}_{\text{rated}} \cdot f(\text{PLR})$$

where, $f(\text{PLR})$ is typically a quadratic or cubic polynomial.

A6.3 Refrigerant Flow Distribution

For parallel evaporators:

$$\dot{m}_{\text{total}} = \sum_{i=1}^{n} \dot{m}_i$$

$$Q_i = \dot{m}_i \cdot (h_{\text{out},i} - h_{\text{in},i})$$

A7. Uncertainty and Sensitivity Analysis

A7.1 Monte Carlo Simulation

For output $Y = f(X_1, X_2, \ldots, X_n)$:

$$E[Y] \approx \frac{1}{N} \sum_{j=1}^{N} f(x_1^{(j)}, x_2^{(j)}, \ldots, x_n^{(j)})$$

$$\sigma_Y^2 \approx \frac{1}{N-1} \sum_{j=1}^{N} \left(f^{(j)} - E[Y]\right)^2$$

A7.2 Sensitivity Indices (Sobol Method)

First-order sensitivity index:

$$S_i = \frac{\text{Var}_{X_i}(E_{X_{\sim i}}[Y \mid X_i])}{\text{Var}(Y)}$$

Total-effect index:

$$S_{Ti} = 1 - \frac{\text{Var}_{X_{\sim i}}(E_{X_i}[Y \mid X_{\sim i}])}{\text{Var}(Y)}$$

A8. Lifecycle Assessment (LCA) Metrics

A8.1 Embodied Carbon

$$\text{EC} = \sum_j m_j \times \text{EF}_j$$

where:

- m_j = mass of material j
- EF_j = emission factor of material j (kg CO_2-eq/kg)

A8.2 Operational Carbon

$$\text{OC} = \sum_{t=1}^{N} E_{\text{annual}}(t) \times \text{EF}_{\text{grid}}(t)$$

A8.3 Total Carbon Footprint

$$\text{TCF} = \text{EC} + \text{OC} + \text{EoL} - \text{R}$$

where:

- EoL = end-of-life emissions
- R = recycling/ recovery credits