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ADVANCED THERMAL MODELING AND HEAT RECOVERY SYSTEMS FOR ENHANCING BUILDING ENERGY SUSTAINABILITY

MAHMOUD AHMED FOUAD
Professor, Mechanical Power Department, Faculty of Engineering Cairo University.
Email: dr.mahmoud.fouad@gmail.com

MOSTAFA ABDELHAMID RIZK
Professor, Mechanical Power Department, Faculty of Engineering Cairo University.
Email: mrizkeqe@gmail.com

ANOUD MOHAMED NAGAF
PhD Student, Mechanical Power Department, Faculty of Engineering Cairo University.
Email: sdsdsdsdsdsdsd@gmail.com

MOSTAFA SHAWKY ABDELMOEZ
Lecturer, Mechanical Power Department, Faculty of Engineering Cairo University.
Email: Mostafashawky11@cu.edu.eg

Abstract

The building sector is responsible for nearly 40% of global energy use and CO_2 emissions, creating an urgent need for sustainable thermal management strategies. This work reviews recent advances in thermal modeling, heat recovery systems, and renewable-integrated HVAC technologies aimed at enhancing building energy efficiency and supporting global decarbonization goals. High-fidelity modeling approaches—including Computational Fluid Dynamics (CFD), Finite Element Method (FEM), and co-simulation platforms—enable accurate assessment of passive systems such as Trombe walls and PCM-enhanced façades, as well as active solutions like geothermal-solar hybrid heat pumps, variable refrigerant flow (VRF) systems, and thermally driven chillers. Parallel developments in heat recovery devices, including energy recovery ventilators (ERVs), drain-water heat recovery (DWHR) units, and flue gas economizers, demonstrate potential seasonal energy savings of 30–60% when integrated into HVAC systems. The review highlights the complementary role of IoT-enabled controls, exergy-based evaluations, and life-cycle assessments in translating modeled potential into real-world performance. Despite rapid progress, research gaps remain in long-term field validation, integration of dynamic occupancy behavior, and techno-economic feasibility at district scales. Addressing these challenges is essential for advancing next-generation thermal systems that deliver scalable, resilient, and net-zero building solutions.

Keywords: Building Energy Sustainability; Thermal Modeling; Heat Recovery Systems; Hybrid Geothermal-Solar Heat Pumps; Variable Refrigerant Flow (VRF); Computational Fluid Dynamics (CFD); Energy Recovery Ventilators (ERV); Phase Change Materials (PCM); District Heating; Smart HVAC Control; Exergy Analysis; Life-Cycle Assessment (LCA).

INTRODUCTION

Advanced thermal modeling and heat recovery systems are central to building energy sustainability, with the potential to significantly reduce energy consumption, operational costs, and carbon emissions. High-fidelity computational tools such as CFD, FEM, and machine learning-based reduced-order models now enable accurate simulations of transient heat and airflow dynamics within building envelopes, including passive systems like Trombe walls and PCM-enhanced fades. For instance, Zhou et al. conducted a CFD-

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based parametric optimization of a phase-change-material Trombe wall and reported better heating energy savings compared to conventional designs in cold climates, with real-world PCMs achieving ~90 % savings [1]. Meanwhile, CFD studies in diverse climatic contexts have highlighted both performance improvements and the need for airflow–thermal coupling in Trombe walls [2], [3].

The building sector is one of the largest consumers of global energy, responsible for approximately 35–40% of primary energy demand and nearly 38% of total CO_2 emissions worldwide [1]. With the accelerating pace of urbanization, the International Energy Agency (IEA) projects that building floor area will double by 2060, a growth equivalent to adding a city the size of Paris to the planet every week for the next four decades [2]. This growth places enormous pressure on energy systems, operational costs, and climate change mitigation efforts. As policy frameworks such as the Paris Agreement and the European Green Deal commit nations to ambitious net-zero targets, reducing energy demand in buildings has become a critical engineering and policy priority.

Within this context, thermal performance optimization—both in terms of energy supply and energy conservation—has emerged as one of the most impactful strategies for sustainable buildings. The majority of building energy consumption is driven by heating, ventilation, and air-conditioning (HVAC) systems, which alone can account for 40–60% of operational energy use in both commercial and residential facilities [3]. High seasonal loads, inefficient thermal envelopes, and static control strategies amplify this demand, underscoring the need for innovative approaches to both supply- and demand-side energy management. Within this context, thermal optimization—through improved design, efficiency, and recovery—offers some of the most immediate and scalable opportunities for reducing building-related emissions.

Three broad strategies have emerged as particularly impactful. First, passive design measures such as Trombe walls, PCM-enhanced façades, and ventilated double-skin systems harness natural processes to regulate indoor climates, reducing the need for active HVAC operation. Second, heat recovery technologies capture and reuse waste energy from exhaust air, wastewater, or flue gases, with potential to reduce seasonal loads by 30–60% when integrated into HVAC systems [4]. Finally, renewable thermal energy integration, particularly through geothermal heat pumps and solar-assisted systems, provides a pathway to sustainable, high-performance heating and cooling.

Recent advances in Computational Fluid Dynamics (CFD), Finite Element Method (FEM), and hybrid data-driven modeling have revolutionized the ability to simulate, optimize, and validate building thermal systems before physical implementation. High-fidelity CFD can now capture complex transient phenomena—such as buoyancy-driven airflow, radiative–convective coupling, and phase-change dynamics—across entire building zones, offering predictive insights into comfort conditions and energy flows [4], [5]. This has been particularly valuable in designing and evaluating passive systems such as Trombe walls, PCM-enhanced façades, and ventilated double-skin façades, which harness environmental conditions to reduce HVAC loads. For instance, recent work by Zhou et al. demonstrated that PCM-integrated Trombe walls could deliver up to 90% heating energy

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savings in cold climates when optimized using CFD-based parametric models [6]. Similarly, Zhao et al. highlighted the importance of coupling airflow and thermal simulations to accurately capture the dynamic performance of Trombe wall systems in varying climates [5].

Alongside passive measures, heat recovery systems have emerged as a complementary pathway to reduce the primary energy footprint of buildings. Waste heat from exhaust air, greywater, flue gases, or industrial processes can be captured and reused for preheating fresh air or domestic hot water. Technologies such as energy recovery ventilators (ERVs), flue gas condensing heat exchangers, and drain water heat recovery (DWHR) units can achieve seasonal energy savings of 30–60% when integrated into HVAC systems. The coupling of these devices with IoT-enabled smart control systems further enables real-time optimization, adapting system operation to occupancy patterns, climatic variations, and energy tariff fluctuations [7]. A third pillar of building thermal sustainability is the integration of renewable thermal energy sources, particularly geothermal heat pumps (GHPs) and solar-assisted systems. GHPs utilize the stable thermal properties of the ground to deliver high coefficients of performance (COPs often exceeding 5), enabling efficient year-round heating and cooling. Hybrid configurations—combining geothermal loops with solar thermal collectors or organic Rankine cycles (ORCs) extend this potential to trigeneration applications, simultaneously producing heat, cooling, and electricity. However, despite promising laboratory and pilot-scale results, real-world deployment is hindered by lack of integrated modeling frameworks, uncertainties in seasonal performance, and limited research on system-level control under dynamic operating conditions[8], [9]. Together, these developments highlight both the urgency and the opportunity: advancing thermal modeling and heat recovery systems is not just a technical challenge, but a cornerstone of sustainable building design in the era of decarbonization.

LITERATURE REVIEW

In the pursuit of decarbonizing the built environment, advanced thermal modeling and heat recovery systems are emerging as pivotal technologies for sustainable building design. This literature review delves into the latest high-performance HVAC innovations—including hybrid geothermal-solar systems, variable refrigerant flow (VRF), multi-source heat pumps, advanced desiccant cooling, and thermally driven chillers—and examines how their thermodynamic performance varies across climate zones, occupancy patterns, and control strategies. The review also explores the role of numerical simulation platforms such as EnergyPlus, TRNSYS, and co-simulation frameworks in optimizing system feasibility and energy savings for both new constructions and retrofits. By synthesizing experimental findings, simulation-based assessments, and thermodynamic analyses, this review aims to inform design optimization while exposing research gaps in real-world adaptability and efficiency.

Recent HVAC Heating and Cooling Technologies

Recent HVAC trends increasingly favor hybrid systems that couple geothermal ground-source heat exchange (GHX) with solar technologies—both thermal and photovoltaic

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(PVT)—creating efficient polygeneration platforms. For instance, TRNSYS-based simulations of hybrid solar–geothermal heat pump systems report COPs up to approximately 4.1–4.3 and notably shorter payback periods—around two years—compared to conventional gas heaters[10]. However, these figures raise questions about contextual variability: why do COP values and payback times differ so widely across studies, and how much do local climate, ground conditions, and system sizing affect these outcomes? Another performance assessment combining photovoltaic systems with ground-source heat pumps demonstrates significant environmental benefits, including CO_2 emissions reductions of nearly 70 tons per year, but the persistently low exergy efficiency (below 10%) underscores a practical limitation—systems may deliver strong environmental benefits while still facing thermodynamic inefficiencies. This suggests that while promising in theory, the real viability of such hybrids depends not only on climate alignment but also on economic scalability, maintenance of complex subsystems, and integration into existing infrastructure. even though overall exergy efficiency remains below 10 percent[11]. These findings highlight the promise of such hybrid systems for sustainable building performance and underscore the importance of thermodynamic and exergy-oriented evaluations. Table 1 below summarizes performance characteristics of different hybrid geothermal-solar HVAC configurations reported in recent literature.

Table 1: Summary of hybrid geothermal-solar HVAC systems performance

System Configuration	Reported COP	Payback Period	CO_2 Reduction
Solar-assisted GHP (TRNSYS, residential)	4.1–4.3	~2 years	–
PV + GHP (simulation, office building)	3.7–4.0	3–4 years	~70 t/year
Geothermal + Solar ORC (pilot-scale)	3.5	4–6 years	45–55 t/year

Table 2 also summarizes the performance of different HVAC systems across different climates as shown.

Table 2: COP performance ranges of different HVAC systems across climates

System Type	Reported COP Range	Typical Climate	Critical Notes
Solar-assisted Ground Source Heat Pump (GHP)	3.7 – 4.3	Cold / temperate climates	High efficiency in stable ground conditions, but performance drops in hot-humid soils due to thermal imbalance.
Photovoltaic + GHP Hybrid	3.5 – 4.0	Office buildings, temperate	Large CO_2 reductions but limited exergy efficiency (<10%), raising questions about thermodynamic quality.
VRF Systems (with solar integration)	3.0 – 4.5	Cooling-dominant climates	Excellent adaptability but electricity dependence can raise costs in heating-dominant regions.
Absorption Chillers (geothermal driven)	1.3 – 1.6	Geothermal-rich / industrial	Viable where low-grade heat is abundant; otherwise cost and scalability barriers dominate.

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Simultaneously, VRF systems continue to stand out for their adaptability and energy efficiency. Thanks to inverter-driven compressors adjusting refrigerant flow to demand, VRFs can slash energy consumption by as much as 55% compared to traditional HVAC setups[12]. Performance can be further enhanced by integrating VRF with solar energy as seen in figure 1—such as photovoltaic-assisted VRF systems modeled in Mediterranean climates—that demonstrate improved seasonal efficiency in both cooling and heating operations[13]. Such integration not only supports electrification and decarbonization goals but also expands VRF applicability across diverse geographies.

Absorption-based systems, driven by geothermal or waste heat, offer another avenue for thermally driven heating and cooling. Systems leveraging 65–90 °C geothermal water can deliver chilled output (~7 °C) for summer cooling and hot water (>47 °C) for heating, with heating-mode COPs exceeding 1.5[13]. Moreover, recent reviews (June 2025) synthesize developments in using geothermal and solar energy—including in district cooling and refrigeration—with absorption chillers as central components in renewable-driven thermal systems[14]. However, their applicability is highly dependent on access to low-grade heat sources, meaning they may thrive in industrial or geothermal resource–rich regions but remain impractical in others. Economic studies also point to high upfront costs, limited commercial suppliers, and slow market diffusion, which restrict widespread deployment despite technical promises. These technologies emphasize cascading energy utilization, enhancing sustainability in large-scale applications.

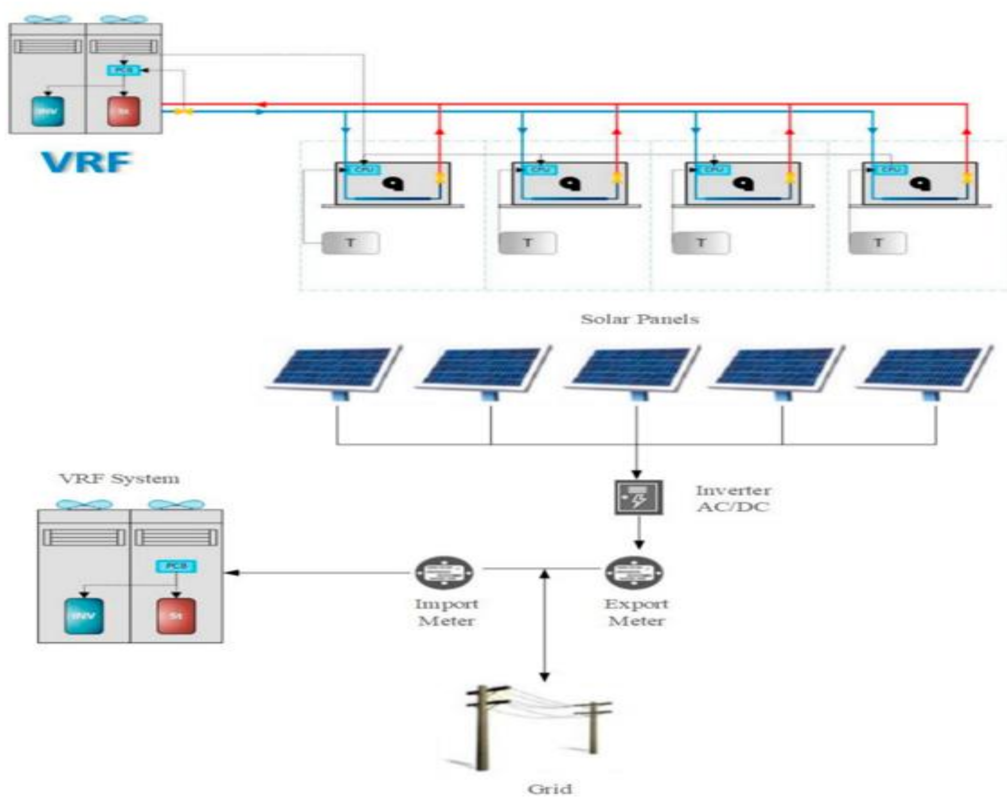

Figure 1: Configuration of a VRF with PV system

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Taken together, these hybrid and thermally driven HVAC technologies lay the foundation for integrating energy recovery solutions—ensuring that energy already within the system is not lost to exhaust, waste streams, or seasonal imbalances. This natural progression leads to the next focus: contemporary heat-recovery technologies that complement and amplify the gains of advanced HVAC configurations.

Understanding and optimizing these advanced HVAC configurations increasingly relies on simulation tools, especially co-simulation. Middleware such as FMI and FMU enable dynamic interplay between EnergyPlus, TRNSYS, MATLAB/Simulink, and other platforms, enhancing predictive modeling of HVAC dynamics, control strategies, and hybrid synergies[15]. Comparative studies also assess simulation accuracy: for instance, TRNSYS and EnergyPlus deliver robust heating/cooling calculations across climatic conditions, supporting their use in exploring parameter effects and peak load behaviors[16]. Yet discrepancies between these platforms often arise due to different default assumptions about boundary conditions, control strategies, and component models, suggesting that conclusions must be carefully contextualized to the chosen tool.

Additionally, detailed dynamic modeling of BIPV/T systems in EnergyPlus—adapted from TRNSYS algorithms—demonstrates the potential for incorporating façade-integrated hybrid systems into whole-building simulation at community scales[17], [18].

Bringing these strands together, hybrid geothermal-solar heat pumps, VRF (including solar-enhanced variants), and thermally driven chillers represent synergistic pathways toward energy-efficient and sustainable HVAC solutions. Their comparative performance—captured through COP, exergy metrics, and emissions—varies significantly based on climate, building use, and system integration design[19]. Simulation platforms with co-simulation enable rigorous evaluation and optimization, yet integrating real-world occupancy variability and smart controls remains a critical challenge. Future research should thus focus on embedding advanced control algorithms and real-time data-driven adaptations into hybrid-system models, closing the gap between theoretical performance and real-world outcomes[20], [21], [22].

Advanced Heat Recovery Systems

With the efficiency of core HVAC systems established, the next step is to explore how heat recovery devices can be seamlessly incorporated, allowing designers to reclaim waste energy that would otherwise be lost, and thereby enhance the overall system performance across all seasons.

Contemporary heat-recovery technologies for buildings—ranging from flue-gas condensing heat exchangers to energy recovery ventilators (ERVs) as simply shown in figure 2, with enthalpy wheels, drain-water heat recovery (DWHR) units, and duct-integrated exchangers—have converged toward a common objective: extract useful sensible and latent energy streams lost to exhausts and wastewater and reintegrate them into space conditioning or domestic hot water systems to reduce primary energy use and emissions [23], [24], [25], [26], [27]. However, reported performance often varies significantly between studies, which raises important questions: do differences stem from

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climate sensitivity, device design, or operational practices? For instance, ERVs show high latent recovery effectiveness in hot-humid climates but deliver reduced benefits in dry winters where frosting and defrost cycles cut performance. This indicates that device performance is not an intrinsic property but one strongly mediated by context.

Systematic reviews show that ERV technologies (both rotary enthalpy wheels and fixed-plate/ membrane types) have matured substantially, and that design innovations (hollow-fiber membranes, improved wheel substrates, and anti-frost strategies) have boosted latent and sensible effectiveness while mitigating cross-contamination and pressure-drop penalties [28], [29]. Parallel advances in flue-gas economizers and condensing heat exchangers for small and medium-scale boilers have demonstrated meaningful recoverable heat fractions and fuel savings, but studies also note that acid-dew-point corrosion and fouling impose practical material and cost constraints. In other words, while laboratory tests show high recovery potential, the durability of components under real operating conditions often becomes the limiting factor for viability. [30], [31]. Meanwhile, DWHR devices and novel multi-layered duct heat exchangers are re-emerging as low-complexity, high-value measures in both new and retrofit contexts, particularly where domestic hot water loads and shower/wastewater flows are substantial .[32], [33], [34]

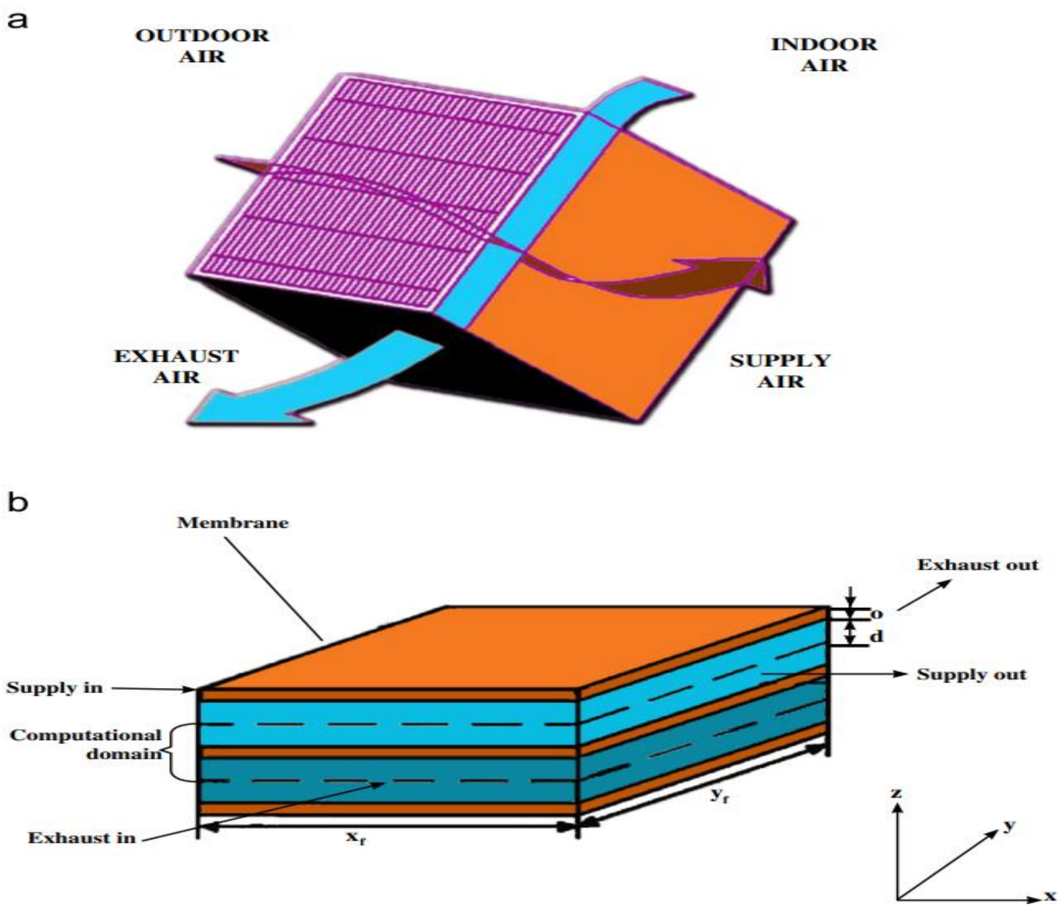

Figure 1: Simple Heat or energy recovery system schematic

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While these recovery devices directly address wasted thermal energy, geothermal heat pumps combined with solar and storage solutions tackle seasonal and load-balancing challenges, bringing the discussion naturally into the domain of renewable hybrid heating and cooling integration.

Across seasons and operating regimes, the performance of these devices is highly situation-dependent, which is why the literature repeatedly stresses climate and operational context in evaluations. ERVs that recover latent energy perform especially well in hot-humid summers (where latent loads dominate) and deliver sensible gains in cold, dry winters; however, icing/frosting and defrost strategies reduce winter effectiveness and can reverse expected savings if poorly controlled [35]. Flue-gas condensing units capture large latent fractions in wet flue streams—driving strong winter heating gains in boiler-dominated systems—but economic and material constraints (acid dew point, particulate fouling) limit how low the flue temperature can be reduced in practice [24], [32]. DWHR units show high instantaneous effectiveness for high-flow showers but face transient penalties and stratification effects that reduce season-averaged gains unless paired with proper piping, mixing and storage strategies [36]. Several comparative and exergy-based analyses in the literature conclude that the net benefit of heat-recovery devices depends on whole-system interactions (fans, pumps, reheat requirements, and controls) and can be overestimated if these auxiliary loads are ignored [37]. Below, table 3 shows the effectiveness, seasonal energy savings, and notable operational limitations—for different heat recovery technologies discussed earlier.

Table 3: Summary of performance of different energy/heat recovery systems

Technology	Typical Effectiveness / Energy Savings	Operational Gain	Key Limitations
ERV / Enthalpy Wheel	60–95% heat recovery (sensible + latent)	40%–60% HVAC load reduction annually	Frost build-up; cross-contamination risks
Flue-Gas Condensing HX	Up to 15–20% of heat recuperated	10–20% fuel savings in winter	Acid-dew-point corrosion; fouling
Drain-Water Heat Recovery (DWHR)	~60% instantaneous; $48–76 annual savings (per unit)	Up to 438 kWh/year energy saved (transient)	Stratification, transient penalties

Because of this context sensitivity, modeling and simulation have become central tools for credible performance assessment and system design. Whole-building energy platforms such as EnergyPlus and TRNSYS support dynamic simulations of ERVs, flue economizers, and DWHR coupled to HVAC plant components, enabling seasonal energy, peak-load, and economic analysis [38][39], [40].

Co-simulation approaches (e.g., EnergyPlus + CONTAM or Modelica couplings) allow concurrent energy, airflow, and contaminant transport modeling so designers can quantify interactions between ventilation heat recovery and indoor air quality under realistic infiltration and occupant schedules [41]. CFD and dedicated component-level models

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enable detailed mapping of heat-transfer and humidity-exchange processes in enthalpy wheels, plate heat exchangers, and drain-water units; these models support improved sizing, pressure-drop optimization, and anti-frost control design, and have been validated in several experimental studies [28].

Recent studies also adopt exergy and life-cycle perspectives in simulation to avoid the pitfall of over-valuing recovered thermal energy when irreversible losses or embodied impacts are considered [37].

Sensor-based modeling, IoT integration and advanced control strategies are the bridge that turns modeled potential into real, operational savings. Demand-controlled ventilation (DCV) using CO_2 or occupancy sensing has repeatedly shown the ability to reduce ventilation energy loads — reported savings vary with building type and occupancy patterns but can be large in intermittently occupied spaces — and when DCV is combined with heat-recovery units the combined savings exceed either strategy alone if controls are coordinated [33], [34].

Integration of Geothermal Heat Pumps

Recent research converges on coupling ground-source/geothermal heat pumps (GHPs or GSHPs) with solar thermal systems (including photovoltaic–thermal, PVT), seasonal thermal energy storage (STES), and hybrid energy loops to overcome both the intermittency of solar supply and the long-term ground thermal imbalance observed in isolated GSHP operation.

Several TRNSYS-based and mixed-tool studies demonstrate that solar-assisted GSHP configurations—such as direct-series, parallel, and PVT-preheat arrangements—enhance the seasonal coefficient of performance (SCOP) by pre-warming or recharging the ground loop and reducing compressor lift in winter, while also enabling free cooling in summer.

Yet, the degree of improvement varies widely—from 15% to over 40% primary energy savings—which suggests that outcomes depend heavily on system sizing, control logic, and climate.[42], [43], [44], [45], [46], [47]. This raises a critical question: are reported gains inherent to technology or are contingent on highly optimized conditions unlikely to be replicated in typical practice?

Figure 3 below shows the hybrid solar–geothermal heat pump polygeneration system that includes a factory building, WWHP, PVT module, GHX, and storage tank. PVT generates thermal energy and electricity simultaneously.

The electricity can be used on the polygeneration site or export grid, and the thermal energy is stored in the PVT buffer tank to be utilized as WWHP heat source in the heating season. The geothermal heat presents relatively warmer than the outside air in winter and colder than the outside air in summer.

Thus, two boreholes of GHX can be utilized as WWHP heat sources in both the heating and cooling seasons.

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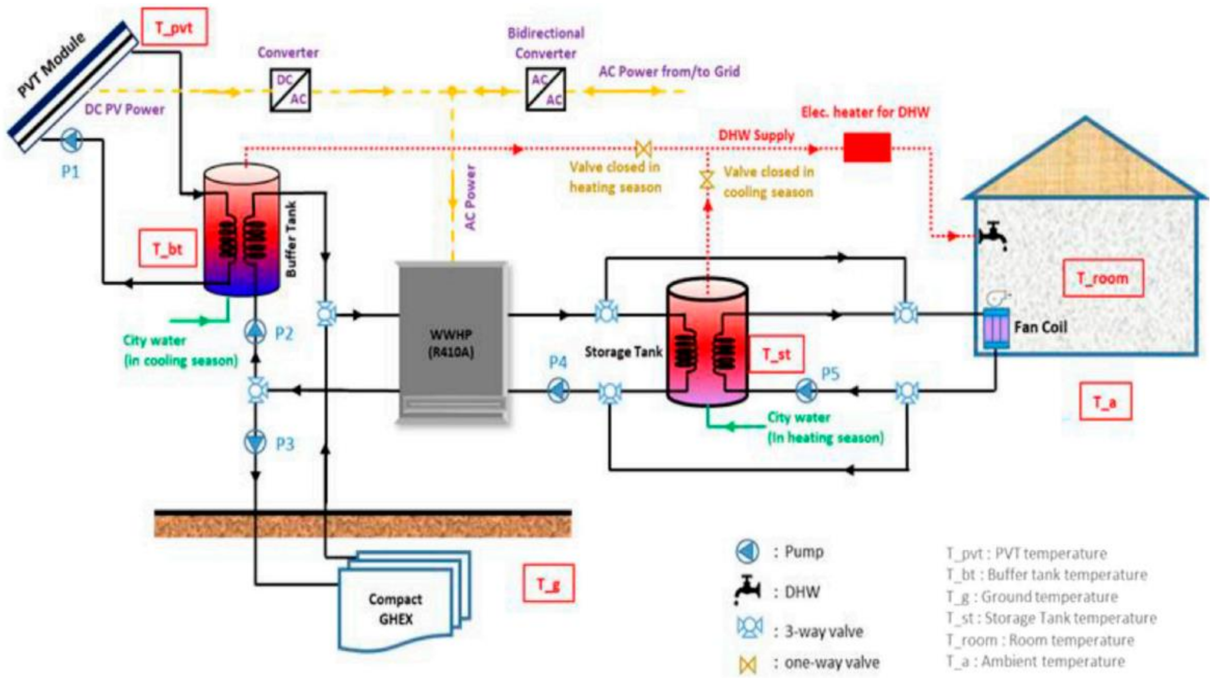

Figure 2: Hybrid solar–geothermal heat pump polygeneration system concept

Figure 3 emphasizes the role of dynamic flow control in optimizing heat exchange. It also serves as a visual cue to why system-level modeling (and simulation tools) must account for loop interactions and control logic to accurately predict seasonal performance. Integrating PVT collectors with GSHPs has grown in popularity because PVT simultaneously supplies heat to the brine loop and electricity to operate pumps or compressors, improving overall exergy and reducing net grid electricity demand. Experimental campaigns and TRNSYS models indicate that optimally controlled PVT–GSHP hybrids can stabilize bore field temperatures, improve long-term ground heat balance, and delay or reverse seasonal ground thermal depletion [48], [49], [50].

Thermal storage—ranging from borehole seasonal thermal energy storage (BTES) to large pit or tank-based STES—has emerged as a key enabler for achieving high renewable fractions in GHP-based systems. Studies coupling GSHPs with large-scale storage demonstrate enhanced operational stability and COP across seasons by shifting surplus summer heat into winter demand, and by reducing short-cycling during part-load conditions. New reduced-order and physics-aware models are making district-scale STES simulation more computationally tractable, enabling techno-economic assessment of multi-building systems. These analyses reveal that storage sizing, stratification management, and control integration strongly influence dispatch strategies and seasonal performance [51], [52], [53], [54], [55].

At the district scale, hybrid thermal loops are merging low-temperature district heating (LTDH) networks with distributed GSHPs and rooftop solar thermal/PVT arrays. Comparative simulation studies indicate that coordinated control of distributed GSHPs,

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central heat pumps, and thermal storage enables high primary energy savings, greater renewable penetration, and the adoption of lower network supply temperatures consistent with 4th- and 5th-generation district heating concepts [56], [57].

System performance under various load profiles and seasonal conditions is highly dependent on system topology, load matching, and climate. In heating-dominant climates, GSHP + solar thermal + STES configurations consistently reduce peak electrical demand and raise seasonal COP by enabling lower source temperature operation and multi-stage heat pump control. In cooling-dominant or mixed climates, such systems can facilitate free cooling and reduced compressor work, provided that summer heat rejection strategies are adequate to prevent long-term ground warming [46], [49], [52]. Dynamic factors such as transient start-up behavior, defrost cycles, variable-speed pumping, and stratification in thermal storage can significantly affect seasonal performance metrics. Several TRNSYS, IDA ICE, and Modelica/Simulink co-simulation studies have shown that steady-state COP estimates may overpredict seasonal efficiency by 5–20% when these transients and control logics are not accounted for [58],[57].

Regarding simulation environments, TRNSYS remains the most widely adopted platform for modelling integrated GSHP–solar–storage systems due to its extensive validated component libraries and proven capability in long-term seasonal simulations [1], [4], [10]. IDA ICE is particularly strong for detailed building energy interactions and HVAC plant integration, making it well-suited for substation modelling in district-scale systems. Modelica-based frameworks (including Buildings and AixLib libraries) excel in control-focused and dynamic operational studies, while MATLAB/Simulink co-simulation is increasingly used to integrate optimization algorithms and advanced supervisory control for hybrid GSHP systems [57], [59], [60].

Finally, taking all factors together, the literature reveals that sustainable building energy strategies cannot be evaluated in isolation. Instead, their performance emerges from a layered interaction: passive envelope measures reduce loads, active HVAC systems deliver efficient thermal conditioning, heat recovery technologies reclaim wasted energy, and advanced modeling/control platforms optimize operations in real time. This interconnected pathway is synthesized in Figure 4, which illustrates how passive, active, recovery, and control elements form a continuous framework for decarbonized building design.

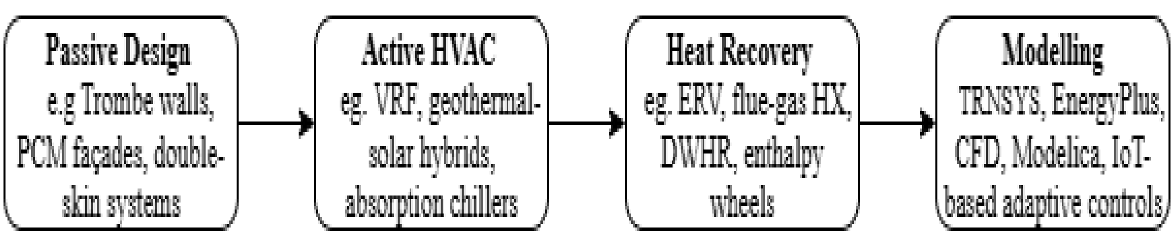

Figure 3: Integrated framework linking passive envelope strategies, active HVAC technologies, heat recovery devices, and modeling/control platforms in sustainable building design

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CFD Modeling Approaches

Finally, the analysis of these technologies would be incomplete without a closer look at Computational Fluid Dynamics (CFD)—the high-resolution toolset that bridges theoretical design and real-world airflow–thermal behavior, enabling engineers to capture fine-scale interactions between systems, spaces, and occupants. Using CFD for HVAC can be used to model on different scales and components as seen in figure 5 below which analyses a Trombe wall with venetian blind structure:

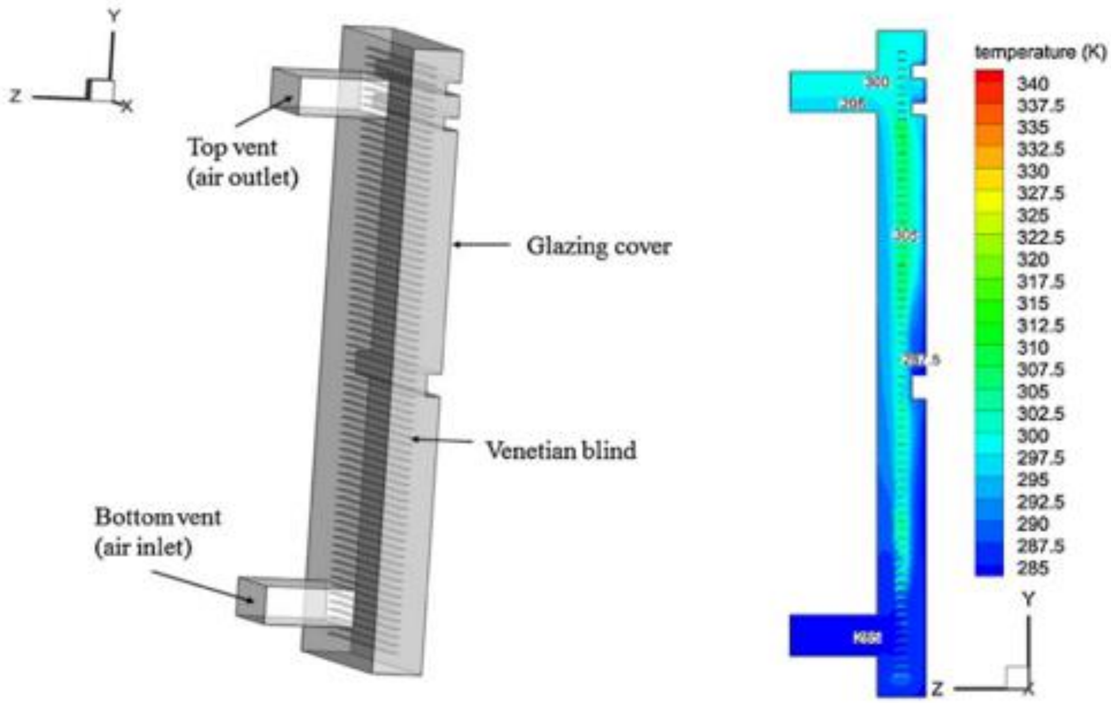

Figure 4: CFD analysis on a Trombe wall with venetian blind structure

Modern building performance modeling increasingly relies on CFD to capture complex interactions between airflow, thermal fields, and heat exchange mechanisms — from active HVAC systems to passive heating/cooling structures and geothermal heat pump (GHP) integrations. The most widely used CFD approaches include steady-state Reynolds-Averaged Navier–Stokes (RANS) models (notably k-ε, k-ω, and SST variants) for overall ventilation and temperature distribution, and transient Large Eddy Simulation (LES) for capturing detailed turbulence and buoyancy-driven phenomena [61], [62], [63]. In passive solar walls or Trombe walls and GHP borehole environments, conjugate heat transfer (CHT) modeling is crucial, as it simultaneously resolves solid conduction and fluid convection—often using the Boussinesq approximation to capture natural convection driving forces [64], [65], [66]. Recent studies highlight that transient LES with CHT domains more accurately simulates morning solar gain and stratification in Trombe walls than RANS, though at a significantly higher computational cost [67], [68]. Table 4 below summarizes various widely used turbulence models and their differences.

Table 4: Comparison of different turbulence models

Model	Typical Use	Strengths	Limitations	Computational Cost
Realizable k-ε	General ventilation, steady airflow	Robust, fast, widely validated	Poor near-wall accuracy, weak for buoyancy	Low
k-ω SST	Indoor airflow with separation	Better near-wall resolution, captures separation	Still time-averaged, less detail in turbulence	Low
LES	Stratification, plumes, transient mixing	High fidelity, resolves turbulence structures	Very expensive, requires fine mesh	High
DES	Door opening, transient HVAC events	Hybrid RANS/LES → balances accuracy/cost	Model sensitive, mesh-dependent	Medium–High

When integrating HVAC with passive structures or GHP loop boundaries, the selection of boundary conditions and radiation models plays a critical role. Coupled radiation–CFD solvers (Discrete Ordinates or Surface-to-Surface methods) are increasingly used to simulate radiative exchange between surfaces and airflow, especially in rooms with glazed envelopes or thermal storage walls [69], [70], [71].

For GHP interactions—such as airflow around underground heat exchangers or plenum mixing zones—mixed turbulence treatments are common: RANS approximates bulk behavior, while LES sections focus on plume behavior near supply air outlets or borehole heat exchanger canals [72], [73]. Transient LES enables capturing recirculation patterns, thermal plumes, and stratification, which are essential for accurate HVAC control strategy evaluation [74].

Solver selection also depends on the modeling objective. For whole-room airflow and temperature distribution in steady heating or cooling, steady RANS is often sufficient and efficient; however, for predicting short-duration events like door openings, occupant-induced convection, or defrost cycles in heat pumps, transient LES or Detached Eddy Simulation (DES) best resolve the unsteady turbulent eddies that drive comfort-relevant flow [75], [76].

The use of Boussinesq approximation simplifies buoyancy modeling and reduces solver complexity but is accurate only for small temperature differences — beyond ~10 K, full density–temperature coupling is preferable [77], [78]. Recent CFD analyses of passive solar air collectors combining natural convection and radiative heating demonstrate that RANS underpredicts peak temperatures by up to 15%, whereas LES delivers better transient capture of daily solar heat gain cycles—but at computational costs 10× higher [69], [79].

Modelling can be done with various ways as stated before either its CFD, TRNSYS, EnergyPlus, or modelica, table 5 below shows the main differences between different simulation tools

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Table 5: Strengths and limitations of key simulation tools

Tool	Strengths	Limitations	Best Use Cases
TRNSYS	Validated component libraries, strong seasonal modeling	Simplified control logic, may overpredict steady-state performance	Hybrid GSHP-solar systems, long-term energy simulations
EnergyPlus	Detailed building-level integration, climate adaptability	Less flexible for new hybrid concepts, slower run times	BIPV/T façade systems, whole-building retrofits
Modelica	Flexible control modeling, dynamic operational studies	Steeper learning curve, fewer validated libraries	Advanced supervisory control, co-simulation with MATLAB
CFD (RANS/LES)	High spatial/temporal fidelity, airflow/thermal coupling	Very high computational cost, often case-specific	Trombe walls, stratification studies, diffuser optimization

Accurate modeling requires careful validation with experimental or sensor-based field data as seen in table 6. Common validation metrics include air temperature stratification profiles, velocity field comparisons (via hot-wire or PIV), and heat flux measurements at surfaces or in the return air.

Several recent chamber and field studies provide benchmark data: e.g., Trombe wall test cells instrumented for internal air stratification and surface flux sampling [80], as well as validation of airflow in radiant-floor zones via infrared thermography paired with CFD [81].

In GHP lab experiments, borehole thermal performance curves derived from instrumentation are used to validate ground temperature fields and simulated flow around the borehole heat exchanger [65], [72].

Validation strengthens model credibility and supports the deployment of CFD-informed control strategies such as dynamic diffuser configuration, zoned air curtains, and intelligent natural ventilation scheduling.

Table 6: Experimental validation methods for CFD HVAC modeling

Parameter Validated	Instrument/Technique	Application
Air velocity field	Hot-wire anemometry, PIV	Room airflow, diffuser jets
Temperature stratification	Thermocouples, IR thermography	Trombe walls, radiant floors
Heat flux	Heat flux sensors, calorimetric plates	Surface energy exchange
Ground temperature (GHP)	Borehole instrumentation, thermal response tests	Soil–pipe heat transfer

Emerging Trends in Thermal Energy

Beyond current hybrid HVAC and recovery solutions, four emerging trends are increasingly shaping the research frontier and real-world applications. First, IoT and AI-driven smart controls are enabling buildings to move from static schedules to adaptive, self-learning systems. By integrating real-time sensor networks, reinforcement learning algorithms, and predictive occupancy models, these controls reduce operational energy while maintaining comfort, with reported savings of up to 25–40% when applied to HVAC–recovery systems [27].

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The convergence of AI and IoT has also facilitated digital twins, allowing predictive maintenance and optimization across entire building portfolios. Second, exergy-based performance evaluation has gained traction as a more holistic metric than traditional COP or primary energy use. Exergy analysis identifies where irreversibility occurs in HVAC, geothermal, and solar-assisted loops, guiding design improvements and control strategies. Studies reveal that while energy efficiency of solar–geothermal systems may appear high, exergy efficiencies often remain below 10–15%, underlining hidden thermodynamic limitations that conventional energy balances overlook. This paradigm shift is pushing system designers toward quality-oriented rather than quantity-only performance metrics.[11]

Third, district-scale hybrid energy loops—linking low-temperature district heating (LTDH), GSHP clusters, and solar-PVT collectors—represent a key pathway toward 4th and 5th generation district heating. Coordinated control of distributed energy sources, borehole storage, and shared thermal networks allows communities to achieve higher renewable penetration, smoother load balancing, and lower distribution losses [55]. These loops blur the line between building-level and city-scale design, requiring integrated modeling platforms and collaborative control strategies.

Finally, life-cycle sustainability metrics (LCA) are being incorporated into building energy system assessments. By accounting for embodied emissions of materials, installation, and maintenance, alongside operational savings, LCA offers a more comprehensive benchmark for long-term sustainability. Recent comparative LCAs demonstrate that while hybrid geothermal–solar systems reduce operational CO_2 by up to 70 tons/year, embodied impacts from drilling, piping, and solar module fabrication can offset part of these benefits unless circular-material strategies are adopted. The integration of LCA into system optimization frameworks is therefore critical for aligning building energy design with global net-zero targets.[58]

Research Gaps and Future Directions

Despite the rapid advancements in hybrid HVAC, geothermal, and solar-assisted recovery systems, several explicit research gaps remain. First, a lack of real-world validation persists while numerous simulation-based investigations using TRNSYS, EnergyPlus, and CFD have demonstrated promising performance outcomes, field-scale demonstrations and post-occupancy evaluations are scarce [27], [31]. This gap raises concerns about the practical reliability of reported energy savings.

Second, there is inadequate integration of dynamic occupancy behavior into system modeling and control. Most studies still assume static or scheduled occupancy patterns, neglecting the stochastic variations of user behavior, plug-loads, and adaptive comfort, which have been shown to significantly alter HVAC loads and energy performance [59]. Bridging this gap requires coupling AI-driven predictive controls with occupant-centric datasets.

Third, material challenges remain underexplored, particularly in the long-term durability of flue gas heat exchangers (e.g., corrosion, fouling) and the stability of phase change

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materials under repetitive cycling. While laboratory tests often confirm initial performance, degradation pathways over 5–10 years of real operation are rarely investigated. This limits confidence in large-scale deployment.[45] Finally, limited techno-economic studies exist at the district/community scale. Although hybrid energy loops and low-temperature district heating (4th/5th generation) have been conceptually validated, few studies incorporate detailed cost–benefit, payback, or life-cycle economic assessments [57].

Such analyses are critical to support decision-making for municipalities and developers seeking to implement next-generation district-scale energy systems. Addressing these gaps through integrated modeling, field demonstration, and life-cycle analysis will be pivotal in translating hybrid HVAC and recovery innovations into resilient, economically viable, and user-centered energy solutions.

CONCLUSION

Advancing thermal modeling and heat recovery systems is central to the global pursuit of net-zero buildings. The building sector's substantial share of energy demand and emissions underscores the urgency of deploying solutions that simultaneously enhance efficiency, resilience, and sustainability.

Passive envelope strategies, advanced HVAC innovations, waste-heat recovery, and renewable thermal integration collectively demonstrate that significant reductions in operational energy use are achievable when guided by robust modeling and intelligent control.

High-fidelity simulation tools and data-driven methods now make it possible to evaluate system interactions under diverse climatic and operational scenarios, ensuring that technologies such as Trombe walls, PCM façades, geothermal loops, and solar-assisted HVAC systems can be optimized before large-scale deployment. When coupled with IoT-enabled adaptive controls, these solutions not only reduce peak loads and energy costs but also improve occupant comfort and resilience to climate variability.

The implications are far-reaching: integrating advanced thermal strategies into building design and retrofit practices can accelerate the transition from incremental efficiency improvements to comprehensive decarbonization pathways.

As nations move toward their net-zero commitments, buildings designed with predictive modeling, energy recovery, and renewable thermal integration will serve as practical testbeds for scalable climate action. Ultimately, achieving net-zero in the built environment will depend on how effectively the insights from simulation and optimization are translated into policies, standards, and market adoption.

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