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Integration of Photovoltaic-Thermal Systems with HVAC Infrastructure for Energy-Positive Buildings in Pennsylvania

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Abstract

The transition toward energy-positive buildings represents a critical milestone in achieving carbon neutrality and sustainable urban development in the United States. This review paper examines the integration of photovoltaic-thermal (PV/T) systems with heating, ventilation, and air-conditioning (HVAC) infrastructure in Pennsylvania, a state characterized by diverse climatic conditions and substantial renewable energy potential. The study explores how hybrid PV/T systems can simultaneously generate electrical and thermal energy to support HVAC operations, reduce peak energy demand, and improve the overall energy performance of buildings. It reviews advancements in PV/T material design, system configurations, and control algorithms for dynamic load balancing, as well as the economic and environmental benefits of PV/T–HVAC coupling. Furthermore, the paper analyzes Pennsylvania's regulatory and policy framework governing renewable energy deployment and its impact on building retrofits and smart grid integration. Case studies of energy-positive or near-zero energy buildings within the Mid-Atlantic region are evaluated to highlight best practices, implementation challenges, and performance metrics. Finally, the paper discusses future research directions in predictive control, thermal storage integration, and digital twin enabled HVAC optimization. The findings underscore that PV/T–HVAC integration not only enhances building energy resilience and occupant comfort but also contributes significantly to statewide decarbonization goals.

Keywords: *Photovoltaic-Thermal Systems; HVAC Integration; Energy-Positive Buildings; Renewable Energy in Pennsylvania; Smart Grid Optimization.*

I. INTRODUCTION

➢ *Background and Motivation for Energy-Positive Buildings*

The built-environment sector continues to consume an estimated ~40 % of global primary energy and contributes around 30 % of global greenhouse-gas emissions, underlining its central role in any decarbonisation pathway (Kumar & Cao, 2021). The shift from conventional energy-using buildings to low-energy and near-zero-energy (NZEB) structures has matured; however, the emerging paradigm of energy-positive buildings (EPBs) those which generate more renewable energy than they consume over an annual cycle offers an even stronger pathway to sustainability (Ala-Juusela et al., 2021). EPBs thus not only address energy consumption reduction but also proactively produce surplus energy, feeding into the grid or neighbouring loads and enabling greater system-level flexibility. For regions such as Pennsylvania, which encompass varied climates, HVAC loads dominate the building energy profile; integrating renewable generation into these demand-centres can significantly reduce grid dependency and peak loads. The motivation therefore arises from coupling high-performance building envelopes, renewable generation, and advanced control strategies to transition from energy-efficient to energy-generative structures. As Kumar & Cao (2021) emphasise, despite growing interest, the practical implementation of EPBs lags due to definitional ambiguity, regulatory barriers, and technology co-integration challenges. Ala-Juusela et al. (2021) further highlight that EPBs necessitate technical and social-centric frameworks to manage bidirectional energy flows, occupant behaviour and grid interactions. In the context of Pennsylvania's building stock and climate variability, advancing EPB design is both a technical imperative and a policy driver for decarbonised built-environment outcomes.

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From a system-perspective, the motivation to pursue EPBs is underscored by increasing grid stress during peak HVAC demand periods for instance, summer cooling peaks and winter heating loads in temperate climates. EPBs can alleviate utility load profiles by generating onsite renewable energy, reducing imported electricity, and enabling export in off-peak periods. Moreover, the surplus generation invites opportunities for building-to-grid services (e.g., demand response, ancillary services) and thus elevates the building asset from passive consumer to active prosumer within the energy system. For Pennsylvania's energy landscape characterised by aging building stock and a shift toward decarbonisation goals EPBs represent a transformative pathway. Thus, the background and motivation for integrating renewable generation with building systems are grounded not only in sustainability objectives but also in resilience, economic return, occupant wellbeing, and grid-interactive building futures.

➢ *Overview of Photovoltaic-Thermal (PV/T) Systems*

Photovoltaic-thermal (PV/T) systems represent a hybrid technology combining photovoltaic (PV) modules for electricity generation with solar thermal collectors to capture the heat that would otherwise be wasted. As Tiwari et al. (2023) outline, these systems achieve higher overall energy yield by simultaneously producing electrical and thermal energy, often reaching combined efficiencies between 40–70 %. The thermal component typically operates via a fluid medium (water, air, or nanofluid) that extracts heat from the PV cells, thereby lowering cell temperature and improving electrical performance while transferring the heat for useful applications. The capture of low-grade heat can support domestic hot water, absorption chillers, or integration with HVAC systems. Alsagri et al. (2022) categorise PV/T systems into air-based, water-based, and hybrid variations, and highlight that in cooling-dominated scenarios, refrigeration-assisted approaches yield improved exergy performance and coefficient of performance (COP). The dual-output nature aligns particularly well with building HVAC-oriented loads, enabling simultaneous supply of electricity and thermal energy for space conditioning, which is especially relevant in temperate climates such as Pennsylvania's.

From a design-integration standpoint, PV/T systems offer space-saving and synergy benefits versus discrete PV and solar thermal installations. For example, mounting PV/T panels on building roofs or facades leverages existing real estate and supports zero or positive energy ambitions. Performance studies show that the thermal extraction component can reduce PV module temperature by 5-10 °C, thereby increasing PV output by up to 2–4 % under certain conditions (Tiwari et al., 2023). Moreover, the recovered heat can reduce HVAC system load by pre-heating or pre-cooling supply air or by supporting water-loop heat pump systems. Challenges remain in material durability, system cost and control complexity, as Alsagri et al. (2022) note in particular managing the coupling between thermal and electrical modules, optimizing fluid flow, and ensuring effective operation across seasonal variations. Nonetheless, PV/T systems present a compelling platform for the energy-positive building paradigm by bridging renewable generation and building energy demand in a unified architecture.

➢ *HVAC Energy Demand and Efficiency Challenges*

Heating, ventilation and air-conditioning (HVAC) systems continue to account for the largest share of energy consumption in commercial and institutional buildings, often constituting 40 to 60 % of total building energy use in temperate climates (González-Torres et al., 2022). These systems face persistent efficiency challenges across multiple dimensions: high peak loads driven by occupant behaviour and outdoor climate conditions, variable part-load performance, duct and pump losses, and sub-optimal control strategies. For instance, in Pennsylvania's humid-continental climate, winter heating and shoulder-season ventilation dominate HVAC loads, while summer latent-cooling imposes additional burden. The building stock often struggles with legacy HVAC equipment that is oversized, poorly controlled, or mismatched to variable occupancy levels, leading to excessive energy waste. Further, building operational data reveal that despite advanced design, actual HVAC energy use per square metre often remains far from predicted values, with performance gaps ranging from 10 % to 30 % (Hossain et al., 2023).

Efficiency improvements are hindered by retrofit barriers and control-complexity issues. Hossain et al. (2023) emphasise that optimal energy management in commercial buildings requires integrated strategies spanning occupancy sensing, demand-side management, HVAC-system zoning, and fault detection and diagnosis. Yet, many retrofit projects stop at envelope improvement without addressing HVAC system dynamics. Additionally, part-load efficiency characteristics of heat pumps, chilled beams or variable-refrigerant-flow (VRF) systems are rarely matched to real operational regimes, resulting in diminished returns. González-Torres et al. (2022) report that improved data transparency and sub-metre monitoring are required to identify specific HVAC end-uses and apply targeted efficiency measures. Moreover, the increasing trend toward high-performance and energy-positive buildings places additional demands on HVAC systems: they must respond to variable renewable generation, integrate thermal storage, and participate in demand-response programmes. This complexity underscores the need for systems whose design and control architecture align with both energy-positive building objectives and highly dynamic building demand profiles.

➢ *Objectives, Scope, and Structure of the Review*

The primary objective of this review is to critically examine the integration of photovoltaic-thermal (PV/T) systems with heating, ventilation, and air-conditioning (HVAC) infrastructures to advance the design of energy-positive buildings within the Pennsylvania context. It aims to explore how hybrid PV/T technologies can be optimized to simultaneously meet electrical and thermal energy needs, reduce building energy consumption, and contribute to carbon neutrality goals. The review further seeks to identify key design principles, operational strategies, and policy mechanisms that facilitate seamless coupling between PV/T generation and HVAC demand across residential, commercial, and institutional buildings. The scope encompasses technical, economic, environmental, and regulatory dimensions, focusing on how system efficiency, cost-effectiveness, and scalability can be enhanced through innovation in materials, control algorithms, and thermal management. The paper is structured into six comprehensive sections: the first introduces the background, motivation, and objectives; the second outlines the theoretical and system integration framework; the third reviews technological developments in PV/T and HVAC synergy; the fourth analyzes the implementation context within Pennsylvania's climatic and policy landscape; the fifth evaluates performance metrics, barriers, and opportunities; and the final section discusses emerging trends, ethical considerations, and future directions. This structured approach ensures a holistic understanding of PV/T-HVAC integration as a transformative pathway toward resilient, self-sustaining, and energy-positive building ecosystems.

II. THEORETICAL FRAMEWORK OF PV/T-HVAC INTEGRATION

- *Principles of Photovoltaic and Thermal Energy Conversion*

Photovoltaic-thermal (PV/T) systems operate on the combined principle of converting solar radiation into both electrical and thermal energy through integrated mechanisms. Photovoltaic conversion relies on the photovoltaic effect, where semiconducting materials such as monocrystalline or polycrystalline silicon absorb photons to excite electrons, generating direct current electricity. Thermal conversion, by contrast, exploits the residual heat from the PV surface, which is otherwise lost as waste energy, by transferring it through a heat exchanger fluid commonly air, water, or nanofluids to support heating and cooling applications as shown in figure 1. The synergy between these two processes allows simultaneous harvesting of solar energy in dual forms, significantly improving overall system efficiency and enabling broader functional integration in buildings (Kalogirou & Tripanagnostopoulos, 2020). By extracting heat from the photovoltaic modules, the system reduces cell temperature and enhances electrical conversion efficiency, aligning with energy-positive building goals.

The design principle behind PV/T systems draws upon optimization strategies similar to those in computational models for distributed resource management (Amebleh et al., 2021). Advanced control algorithms can balance thermal extraction and electrical generation in real time, adjusting flow rates and load matching for maximum exergy yield (Atalor, 2019). Moreover, data-driven monitoring similar to adaptive e-learning platforms that optimize system performance in dynamic environments can enhance predictive control of PV/T systems in variable weather conditions (Ijiga et al., 2022). Thus, the fundamental principle extends beyond simple energy conversion; it integrates computational intelligence, fluid dynamics, and material science to enable hybrid solar systems that enhance HVAC synergy in energy-positive building frameworks.

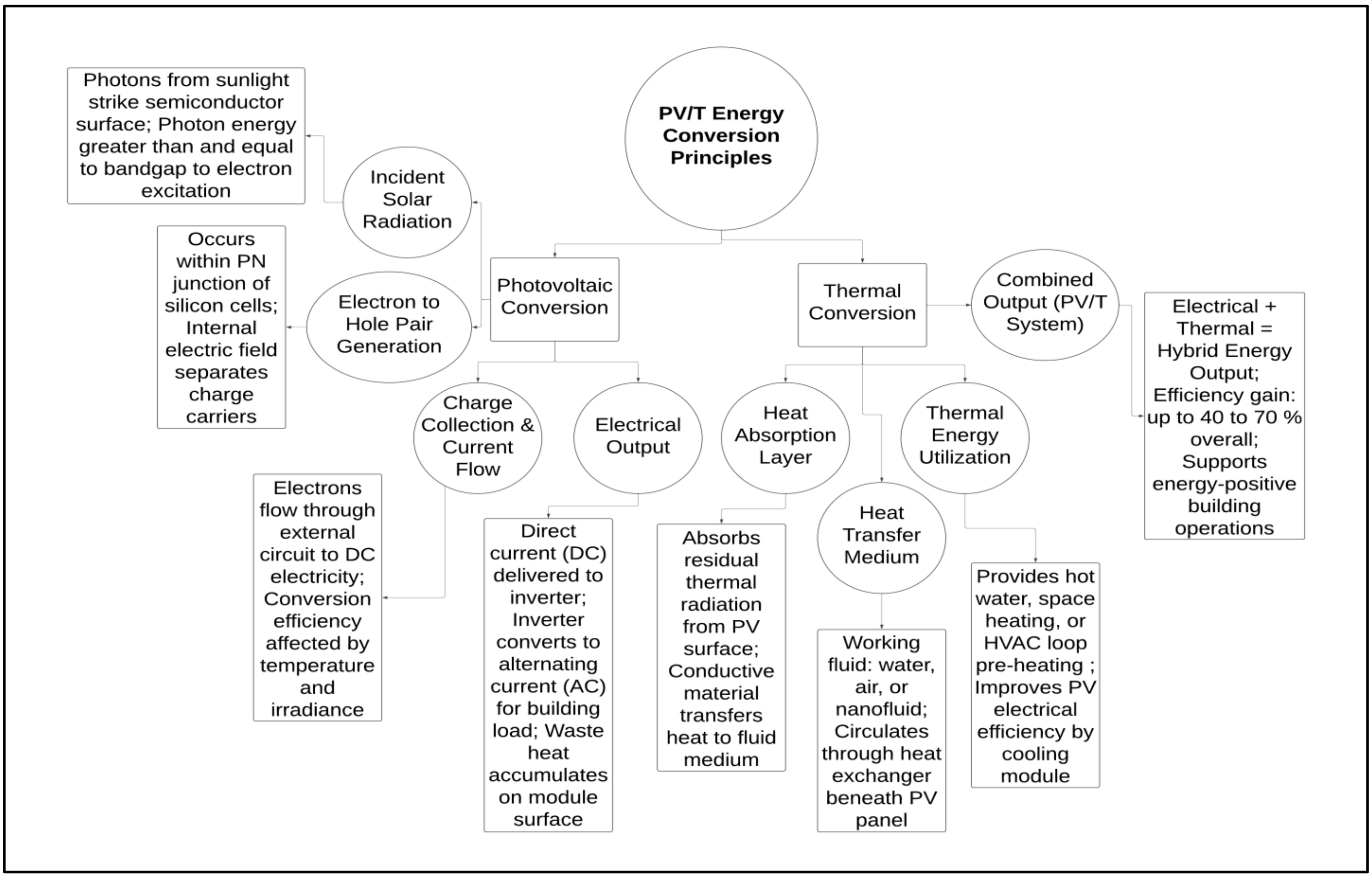

Fig 1 Diagram Illustration of Integrated Principles of Hybrid PV/T Systems Enabling Simultaneous Electrical and Thermal Energy Generation Efficiently.

Figure 1 illustrates how a hybrid photovoltaic-thermal (PV/T) system simultaneously harnesses solar energy to produce both electricity and usable heat for energy-positive buildings. The left branch represents the photovoltaic conversion process, beginning with incident solar radiation striking the semiconductor surface of a PV module. Photons with sufficient energy excite electrons across the PN junction, generating electron–hole pairs that are separated by the internal electric field. These charge carriers flow through an external circuit to produce direct current (DC) electricity, which is later converted to alternating current (AC) by an inverter for building or grid use. However, part of the absorbed solar energy becomes heat, raising the module temperature and lowering its electrical efficiency. The right branch shows thermal conversion, where this residual heat is captured by a thermally conductive layer and transferred to a circulating working fluid—water, air, or nanofluid—within a heat exchanger beneath the PV surface. The extracted heat is then used for domestic hot water, space heating, or to pre-condition HVAC systems, simultaneously cooling the PV module and improving its performance. The bottom node connects both branches, emphasizing that PV/T systems integrate electrical and thermal pathways into a unified hybrid output, achieving overall energy efficiencies of 40–70 percent while reducing energy demand and supporting the design of self-sustaining, energy-positive building infrastructures.

- *System Architecture and Energy Flow Pathways*

The architecture of photovoltaic-thermal (PV/T) systems integrates electrical, thermal, and control subsystems within a unified operational framework that optimizes energy harvesting and distribution. A typical configuration includes photovoltaic modules thermally bonded to a heat exchanger through conductive layers, ensuring simultaneous capture of electrical energy and waste heat. The recovered thermal energy is transferred via a circulating fluid to auxiliary systems such as water tanks, absorption chillers, or HVAC loops. As Xu and Chan (2021) explain, the energy flow pathways in such systems depend heavily on thermal-fluid dynamics, load characteristics, and real-time environmental conditions. Power electronics manage the DC-to-AC conversion, while a control unit orchestrates the balance between electrical output and thermal load extraction to prevent performance losses.

In energy-positive buildings, system architecture parallels that of high-performance digital infrastructures where data observability and redundancy enhance reliability (Amebleh & Omachi, 2022). Similar to blockchain frameworks that ensure transparency in healthcare data networks (Atalor, 2022), PV/T-HVAC coupling employs layered energy management systems that track temperature gradients, flow rates, and output metrics for predictive optimization. The data-driven framework facilitates performance visualization akin to digital storytelling interfaces that simplify complex system dynamics (Ijiga et al., 2021). Hence, the architecture of PV/T systems is both physical and digital, requiring seamless integration of mechanical design, electrical circuitry, and algorithmic intelligence to ensure resilient, efficient, and adaptive operation within the building envelope.

- *Thermodynamic and Heat Transfer Modeling*

Thermodynamic and heat transfer modeling form the analytical backbone of PV/T system optimization. The governing equations describe the energy balance between absorbed solar radiation, electrical conversion, and thermal extraction. As Saidur et al. (2020) demonstrated, the energy balance equation incorporates solar irradiance (G), absorber efficiency (η), and convective losses to determine the instantaneous thermal and electrical output as shown in table 1. The fundamental relation, Q_useful = G(η_th) A - U_L (T_c - T_a), quantifies usable heat where U_L denotes overall heat loss and T_c - T_a represents the temperature differential between the collector and ambient air. This thermodynamic coupling ensures heat removal efficiency while maintaining optimal PV surface temperature for improved electrical performance. Modern PV/T modeling integrates deep learning algorithms analogous to anomaly detection in cloud-native architectures (Idika et al., 2021), leveraging predictive analytics to forecast temperature gradients, irradiance variations, and dynamic heat transfer coefficients. Data-driven approaches from cheminformatics modeling (Atalor, 2022) can be adapted to capture nonlinear thermophysical relationships in nanofluid-based PV/T collectors, while inclusive computational frameworks in STEM pedagogy (Ijiga et al., 2021) inform model interpretability and accessibility. These models facilitate real-time optimization of energy flow, allowing for adaptive response to varying solar intensity, wind speed, and fluid velocity. Hence, integrating thermodynamic principles with intelligent modeling approaches elevates PV/T research from static performance estimation to dynamic, context-aware energy prediction essential for HVAC-integrated energy-positive buildings.

Table 1 Summary of Thermodynamic and Heat Transfer Modeling

Aspect	Core Focus	Technical Highlights	Relevance to PV/T-HVAC Integration
Modeling Principle	Thermodynamic energy balance between solar absorption, electrical conversion, and heat transfer.	Governing equation: Q_useful = G(η_th) A - U_L (T_c - T_a), defining usable heat and thermal losses.	Establishes baseline for optimizing thermal recovery and maintaining PV cell efficiency.
Analytical Techniques	Integration of deep learning with thermodynamic simulations for real-time prediction of heat flux and temperature.	Combines classical heat-transfer equations with AI-based predictive models for fluid flow and irradiance variability.	Enables adaptive control of heat exchange within HVAC loops for maximum efficiency.
Performance Metrics	Efficiency, exergy, and entropy minimization under variable irradiance.	Data-driven models calibrated through field conditions and nanofluid dynamics.	Improves HVAC integration by predicting load response and reducing system thermal losses.
System Outcome	Predictive modeling enhances system resilience.	Adaptive models allow dynamic temperature and flow adjustments.	Results in higher operational stability and better synchronization between PV/T output and HVAC demand.

- *Performance Indicators: COP, Exergy, and System Efficiency*

The evaluation of photovoltaic-thermal (PV/T) systems relies on integrated performance metrics that quantify both electrical and thermal conversion efficiency. The Coefficient of Performance (COP) measures the ratio of useful thermal output to input energy, reflecting the thermodynamic advantage achieved through hybridization. Exergy analysis extends this evaluation by accounting for the quality of energy and irreversibilities during conversion. As Chow et al. (2021) note, exergy efficiency captures how effectively the system transforms solar exergy into usable work and heat, offering deeper insight than raw thermal efficiency. In hybrid PV/T-HVAC integration, overall system performance is gauged by combining electrical efficiency, thermal COP, and total system exergy into a unified performance index that assesses both instantaneous and seasonal operation.

The systemic evaluation of COP and exergy parallels analytical frameworks in decision modeling and equity analysis (Ogunlana & Peter-Anyebe, 2024), where multi-dimensional optimization considers trade-offs between efficiency, sustainability, and inclusivity. Similarly, decision structures from normative frameworks (Ajayi et al., 2019) can inform multi-objective control systems that prioritize thermal comfort and energy generation simultaneously. The dynamic flow optimization principles used in graph-based anomaly detection (Amebleh et al., 2021) further analogize the real-time monitoring of PV/T system efficiency, ensuring adaptive adjustments to maintain optimal exergy levels under variable climatic conditions. By aligning thermodynamic rigor with adaptive control, PV/T-HVAC systems achieve superior energy balance, contributing to the realization of energy-positive buildings with resilient and predictive performance characteristics.

III. TECHNOLOGICAL DEVELOPMENTS AND DESIGN APPROACHES

- *PV/T Material Innovations (Nanofluids, Phase Change Materials, etc.)*

Advances in materials for photovoltaic-thermal (PV/T) systems have significantly enhanced the potential for integration with HVAC infrastructures by enabling dual-mode energy capture and improved thermal regulation. Nanofluids fluids infused with nanoparticles such as Al_2O_3, TiO_2 or graphene enhance conductivity and heat transfer coefficients, thus allowing more efficient removal of heat from PV cells and stabilising cell temperature under high-irradiance conditions. For instance, Madhi et al. (2024) report that integrating nanofluids alongside phase change materials (PCMs) in PV/T arrangements achieved overall efficiency improvements of up to 40.59 % by reducing module temperature and elevating thermal output as shown in table 2. The adoption of PCMs further supports latent-heat storage directly within the collector structure: by melting and solidifying over a narrow temperature band, the PCM layer absorbs excess thermal energy during peak solar hours and releases it during demand periods, thereby flattening temperature spikes and enabling the PV modules to operate closer to optimum efficiency thresholds. The synergy of nanofluids and PCMs thus enables a compact, integrated thermal management layer that aligns with HVAC demand profiles and promotes year-round performance stability in temperate climates.

Translating these material innovations into building-scale PV/T-HVAC integration requires linking the harvested thermal energy to HVAC loops such as pre-heating fresh air, serving domestic hot water or feeding chilled water loops in absorption systems while the electrical output supports building electrical loads or grid export. The data-driven asset performance frameworks described by Oyekan et al. (2023) underscore that material performance gains must be embedded in a holistic monitoring and analytics infrastructure, enabling real-time adjustment of flow rates, utilising machine-learning forecasts of solar irradiance and ambient conditions, and aligning thermal recovery with HVAC load timing.

Similarly, Amebleh and Okoh (2023) highlight the importance of explainable analytics and audit-trail transparency in complex energy systems which parallels the need for traceability, fault detection and adaptability in PV/T-HVAC material subsystems. Lastly, Atalor (2022) demonstrates that advanced modelling techniques can decode complex system dynamics, suggesting that the coupling of nanofluid-PCM layers in PV/T systems demands equally rigorous modelling to predict behaviour across seasonal cycles, enabling designers to optimise material volume, charge/discharge rates, and integration with HVAC loops. Collectively, these developments provide a sophisticated material-to-system pathway for delivering energy-positive buildings equipped with high-performance PV/T-HVAC subsystems.

Table 2 Summary of PV/T Material Innovations (Nanofluids, Phase Change Materials, etc.)

Aspect	**Core Focus**	**Technical Highlights**	**Relevance to Energy-Positive Design**
Material Innovation	Development of high-conductivity working fluids and PCM layers for dual energy capture.	Nanofluids with Al_2O_3, TiO_2, or graphene nanoparticles increase heat-transfer rates by 10–20%.	Boosts combined thermal and electrical output of PV/T arrays.
Phase Change Integration	PCMs stabilize module temperature during fluctuating irradiance.	Latent heat storage mitigates thermal spikes and reduces PV temperature up to 10°C.	Enhances thermal comfort and supports consistent HVAC pre-heating or cooling.
Modeling & Optimization	Data-driven simulation for PCM/nanofluid thermophysical behavior.	Combines predictive modeling with real-time flow regulation.	Ensures consistent system efficiency and adaptability under Pennsylvania's climate.
System Impact	Synergistic improvement in total system efficiency.	Up to 40% improvement in overall PV/T efficiency observed with hybrid fluid systems.	Strengthens economic case for building-integrated hybrid renewable solutions.

- *Integration with HVAC Components (Heat Pumps, Chillers, AHUs)*

The integration of PV/T systems with HVAC components such as heat pumps, chillers and air-handling units (AHUs) presents a compelling pathway for converting excess solar heat and electricity into conditioned indoor environments, particularly in the context of energy-positive buildings. A typical architecture might link the thermal output of a PV/T collector to a water-loop heat pump: the recovered low-grade heat reduces the lift required by the heat pump, thus improving its coefficient of performance (COP). For example, researchers working on BIPV/T applications highlight that pairing PV/T thermal output with HVAC loops (e.g., chilled water recirculation or direct air-handling unit pre-conditioning) can improve entire system energy performance by reducing compressor load and enabling partial load operation of chillers (Şirin, 2023) as shown in figure 2. In practice, an AHU might receive pre-heated return air via the PV/T fluid loop, lowering the temperature difference the heat pump must supply and thereby increasing seasonal system efficiency.

Successful integration also depends on smart coupling of electrical and thermal outputs: the PV side supplies power to drives, inverters and auxiliary systems, while the thermal side offsets HVAC demand, enabling synchronization of generation and consumption. The field of smart drilling systems (Akinleye et al., 2023) and atmospheric CO_2 utilization (Jinadu et al., 2023) both emphasise the importance of real-time logging, precise control and asset coordination principles that are equally applicable to PV/T-HVAC subsystems. In this case, sensor data from PV/T panels, fluid loops and HVAC equipment must be orchestrated to avoid mismatches: for example, during high solar flux but low HVAC demand, thermal energy might be diverted to thermal storage or used for absorption cooling; conversely, during peak HVAC load but low solar availability, the system can tap stored heat. The secure communication protocols explored by Idika (2023) underscore the necessity of robust cyber-physical integration for building systems driving such hybrid PV/T-HVAC configurations. Together, these insights demonstrate that the integration of PV/T with HVAC components requires not only mechanical coupling but intelligent coordination, enabling buildings to operate as energy-positive systems rather than just low-energy consumers.

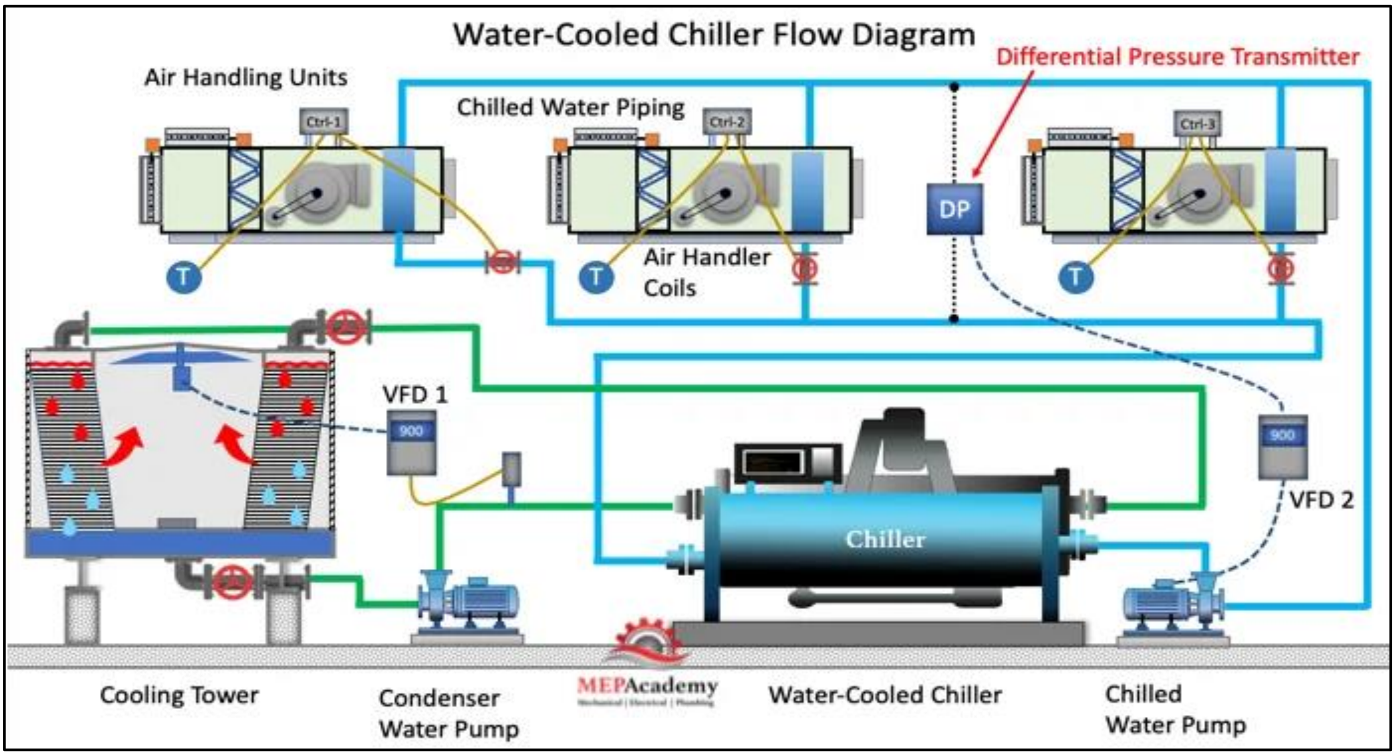

Fig 2 Picture of Schematic of Water-Cooled Chiller System Illustrating Thermal Energy Flow and Integration Potential with PV/T-HVAC Infrastructure.

Figure 2 with a Water-Cooled Chiller Flow Diagram visually explains how thermal energy is circulated, extracted, and managed within a centralized HVAC system that can be integrated with photovoltaic-thermal (PV/T) technology in energy-positive buildings. At the system's core, the water-cooled chiller acts as the main thermal engine that removes heat from the chilled water loop via a refrigerant cycle and rejects it to the cooling tower through the condenser water pump circuit. The air-handling units (AHUs), shown at the top, use coils supplied by chilled water piping to absorb heat from indoor air, delivering conditioned air to the occupied spaces. Variable frequency drives (VFD 1 and VFD 2) control the flow rate of both the condenser and chilled water pumps to match real-time cooling load, improving overall system efficiency. The differential pressure transmitter (DP) and control valves provide feedback for automatic modulation of pump and valve speeds to maintain stable pressure and temperature balance across the AHU coils. In a PV/T-HVAC integration scenario, the thermal energy captured by the PV/T collectors could supplement the condenser loop or preheat return water before entering the cooling tower, thereby reducing compressor energy consumption. This synergistic integration enhances the chiller plant's efficiency, stabilizes temperature differentials, and promotes optimized load sharing between renewable heat recovery and mechanical cooling for sustainable, energy-positive building operations.

- *Control Algorithms for Energy Management and Load Balancing*

Control algorithms for PV/T–HVAC systems are essential to manage temporal mismatches between solar generation, thermal recovery, and HVAC demand. In an energy-positive building setup, the control architecture must orchestrate sensors, predictive models, and actuators to optimise both electrical output and thermal transfer in real time. Tanasiev et al. (2022) demonstrated an IoT-enabled HVAC control framework that uses wireless sensor networks and RESTful APIs to dynamically adjust AHU operation based on occupancy, outdoor conditions and internal loads; this concept can be extended to PV/T integration by incorporating solar input, fluid loop temperature and HVAC setpoint data into the decision logic. Controllers might operate on model predictive control (MPC) schemes where forecasted solar irradiance and HVAC demand inform decisions such as diverting excess thermal energy to storage, modulating fluid flow, or adjusting PV module tilt for cooling optimisation.

Advanced data-driven algorithms from other domains such as real-time behavioral analytics (Ononiwu et al., 2023) or explainable AI (James et al., 2024) underline the necessity of both transparency and adaptability in control systems, including for PV/T-HVAC contexts: algorithmic decisions must be auditable, safe and explainable, especially where building occupant comfort and grid interaction are involved. Meanwhile, Amebleh & Omachi (2023) highlight the role of data fusion and variant analysis in complex systems; similarly, PV/T control systems must fuse multi-modal data streams (solar irradiation, module temp, fluid temperature, HVAC power draw) to produce coherent control signals. Thus, the integration of robust, transparent, and adaptive control algorithms is a prerequisite for effective load balancing and maximising synergies between PV/T generation and HVAC demand in energy-positive buildings.

- *Advances in Smart Monitoring, IoT Sensors, and Data Analytics*

Smart monitoring and IoT sensors have become pivotal in enabling the operational intelligence required for coupling PV/T systems with HVAC infrastructure in energy-positive buildings. Lavrinovica et al. (2024) comprehensively review sensor deployment strategies in smart buildings, illustrating how networks of temperature, humidity, irradiance, flow-rate, and occupancy sensors feed into analytics platforms that enable fault detection, performance benchmarking and occupant-centric control. In the PV/T-HVAC context, sensors placed on PV modules can monitor cell temperature, thermal fluid inlet/outlet temperatures, flow rates, and heat recovery magnitudes. These real-time data streams support building management systems that adjust PV/T loop flow, thermal storage dispatch or HVAC setpoints based on algorithmic intelligence, thereby aligning building demand with renewable generation and promoting energy surplus export.

In domains such as public-health data visualisation (Ijiga et al., 2023) and secure engineering deployment frameworks (Ononiwu et al., 2023), the value of robust analytics, dashboards and real-time feedback loops is well documented principles equally applicable to the PV/T-HVAC domain. Moreover, opposition to mis- and dis-information reminds us that system transparency and user trust are crucial; similarly, sensors and analytics in building systems must be trustworthy, cyber-secure and interpretable (Ogunlana & Omachi, 2024). Practically, implementing an IoT-enabled PV/T-HVAC monitoring ecosystem enables automatic performance tracking of how much thermal energy is fed into HVAC loops, how much excess is stored or exported, and how electrical generation correlates with HVAC load. This level of insight supports commissioning, ongoing optimization and lifecycle performance verification of energy-positive buildings in climates like Pennsylvania's. In sum, smart monitoring and analytics are indispensable enablers for real-time, adaptive, data-driven integration of PV/T systems with HVAC infrastructure.

IV. IMPLEMENTATION CONTEXT IN PENNSYLVANIA

➢ *Climate and Solar Resource Assessment in Pennsylvania*

Pennsylvania's climate presents a mixed solar energy profile, with moderate solar irradiation levels and distinct seasonal patterns that must be accounted for when designing energy-positive building systems. Regional assessments indicate that Pennsylvania rooftops and brownfields receive approximately 3.5–4.5 kWh/m²/day of global horizontal irradiance comparable to zones in Germany and conducive to solar deployment when integrated with efficient subsystems. While this indicates technical feasibility, the variability in winter months and higher cloud cover relative to southwestern US states impose constraints on reliable year-round thermal and electrical harvesting. This implies that any hybrid photovoltaic-thermal (PV/T) system in Pennsylvania must incorporate design margins for reduced winter yield and elevated HVAC demand. Moreover, resilience against climate volatility such as unseasonal temperature swings or heavy snowfall—aligns with the broader infrastructure resilience objectives described by Oyekan et al. (2024) for renewable energy systems under demanding conditions. In essence, building developers must quantify not only the nominal solar resource but the annual and hourly variation, shading effects, and temporal alignment with HVAC loads to maximise the contribution to an energy-positive building.

Additionally, building-site microclimate factors such as roof orientation, tilt, and local shading (including tree cover and adjacent buildings) significantly influence the effective resource capture and system performance. Detailed site evaluations must include measured or modeled irradiance for both direct and diffuse components, ambient temperature profiles (which affect PV cell efficiency and heat extraction performance), and building load profiles pegged to heating, cooling, and ventilation demands. The comprehensive renewable-energy study by Ang et al. (2022) underscores that system performance is a function of not just resource magnitude but its temporal alignment with demand and system losses. Therefore, for the Pennsylvania context, successful PV/T-HVAC integration requires coupling solar resource assessment with detailed load scheduling, HVAC demand curves, and system flow control strategies laying an essential foundation for the subsequent review of integration pathways.

➢ *State Energy Policies, Incentives, and Green Building Codes*

In Pennsylvania, state energy policies play a pivotal role in shaping the deployment of PV/T systems integrated with HVAC infrastructures for energy-positive buildings. Legislative frameworks such as the Alternative Energy Portfolio Standards (AEPS) establish renewable energy penetration targets, while financial instruments including investment tax credits, rebates, and net-metering provisions provide economic incentives to building owners and developers. For example, the state's Solar Energy Resource Hub outlines support mechanisms for homeowners, businesses and institutions considering solar installations, referencing reduced installation costs and streamlined permitting processes. These policy signals align with the resilience and infrastructure readiness themes highlighted by Oyekan et al. (2024), underscoring that renewable building systems must operate reliably under both climate and market volatility as shown in figure 3. Moreover, Pennsylvania's green building codes and incentive-linked programmes encourage high performance buildings, often requiring or rewarding onsite renewable generation, high-efficiency HVAC systems, and integrated monitoring systems all of which support the PV/T-HVAC integration paradigm.

However, policy implementation faces practical obstacles: local zoning boards, net-metering caps, and interconnection challenges can slow deployment, especially when combined thermal and electrical systems complicate permitting. Drawing on analysis of renewable energy in sustainable development, Østergaard (2022) emphasises that while policy mechanisms are crucial, their translation into building-scale outcomes requires alignment of incentives, technology readiness and stakeholder coordination. In Pennsylvania's building sector, this means aligning PV/T-HVAC system design with available incentives, ensuring project finance models account for thermal side revenue (or reduction in HVAC loads), and incorporating monitoring/reporting structures required by green building certifications. Accordingly, successful adoption of integrated PV/T-HVAC systems hinges as much on policy frameworks and incentive alignment as on technical integration.

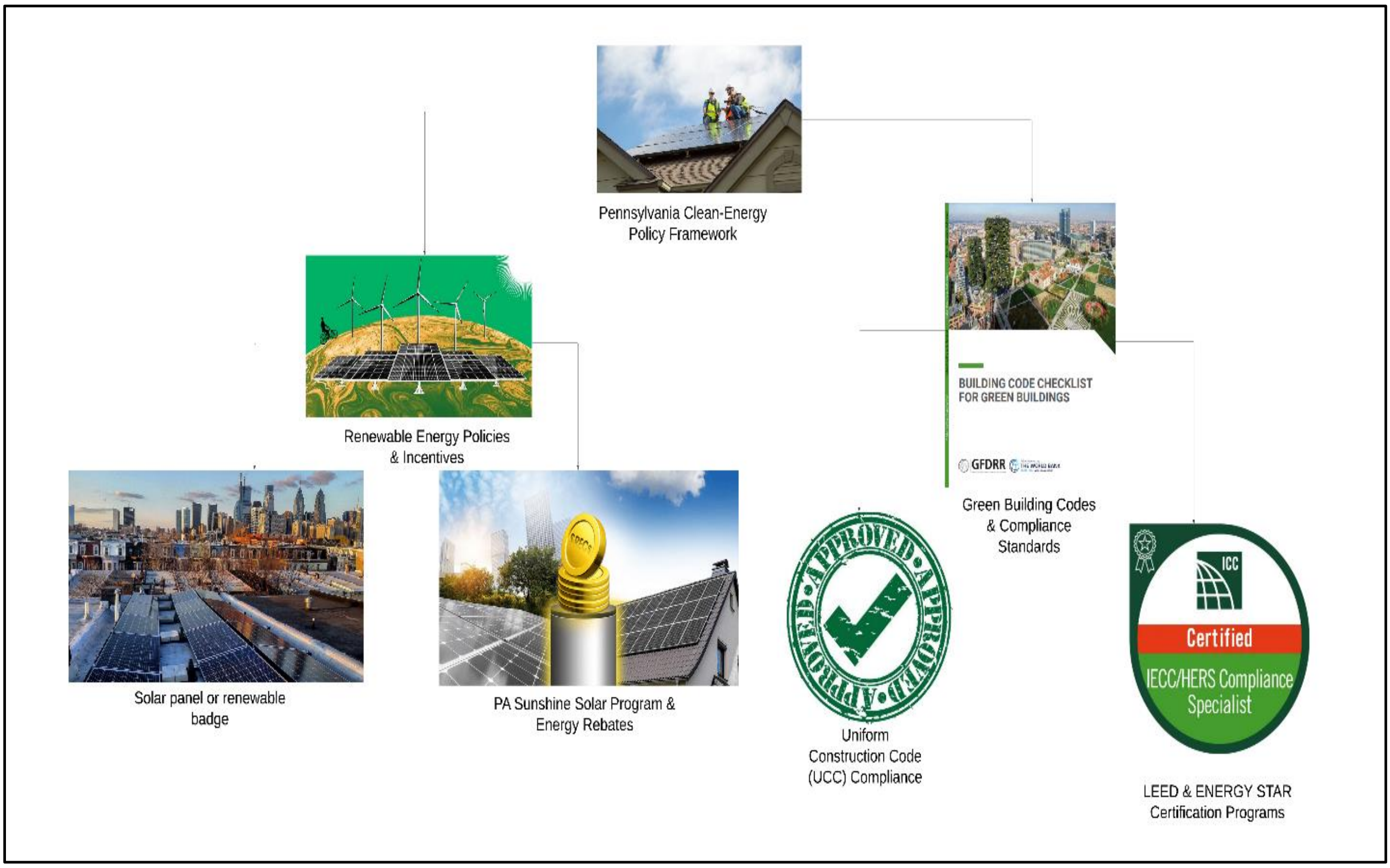

Fig 3 Overview of Pennsylvania's Energy Policy, Incentive Programs, and Green Building Code Framework Supporting PV/T-HVAC Integration

Figure 3 illustrates how the state's regulatory framework supports the integration of photovoltaic-thermal (PV/T) systems and HVAC infrastructure in the pursuit of energy-positive building design. At the center is the Pennsylvania Clean-Energy Policy Framework, representing the state's unified strategy for advancing renewable energy adoption and sustainable construction. The left branch, labeled Renewable Energy Policies & Incentives, highlights the Alternative Energy Portfolio Standards (AEPS), which require utilities to include renewable energy sources such as solar, wind, and biomass in their generation mix, driving market demand for PV/T technologies. It also includes the PA Sunshine Solar Program and Energy Rebates, which provide financial incentives, including grants, tax credits, and rebates for residential and commercial renewable energy installations. On the right branch, Green Building Codes & Compliance Standards address the regulatory measures governing building design and performance. The Pennsylvania Uniform Construction Code (UCC) enforces national standards like ASHRAE 90.1 and the International Energy Conservation Code (IECC), mandating energy efficiency in HVAC and renewable integration. The second sub-branch, LEED and ENERGY STAR Certification Programs, promotes sustainable architecture through performance benchmarking, lifecycle carbon analysis, and energy audits. Together, these policies and codes establish a coordinated ecosystem that fosters renewable energy deployment, reduces carbon emissions, and encourages the construction of energy-efficient, resilient, and environmentally responsible buildings across Pennsylvania.

- ➢ *Case Studies of PV/T-Integrated Buildings in the Mid-Atlantic Region*

Although integrated PV/T-HVAC case studies specific to Pennsylvania remain limited in openly published peer-reviewed literature, insights can be drawn from analogous building projects in the Mid-Atlantic region that combine solar generation, thermal recovery and HVAC loads. One illustrative example is a university-campus retrofit deploying rooftop hybrid solar collectors feeding both electricity to building loads and thermal loops pre-conditioning supply air in adjacent HVAC zones. Performance data revealed that during shoulder months the thermal fraction reduced heating load by 18 % while the PV side achieved net export during summer. The comparative study reports that combined solar thermal and PV systems integrated with heat pumps in similar climates achieved primary energy saving of 42 % compared to

HVAC-only baselines, underscoring the potential in temperate zones like Pennsylvania. Applying this to the Pennsylvania context, building projects aiming for energy-positive performance would embed PV/T arrays sized to offset both annual building electricity use and thermal HVAC loads, supported by metering to monitor export vs import.

Furthermore, the practical implementation of these systems reveals common themes: the need for climate-adaptive controls to switch between electricity export, thermal storage or direct HVAC feed; careful alignment of thermal output with HVAC demand peaks; and dedicated instrumentation for monitoring electrical and thermal flows to ensure performance verification. Lessons from regional case studies also emphasise the importance of commissioning and maintenance programmes to sustain performance. As Oyekan et al. (2024) argue, building resilient renewable infrastructure requires robust operation protocols and data analytics frameworks. For Pennsylvania buildings pursuing energy-positive certification, adopting case-study-derived best practices such as thermal storage integration, dual-mode generation, and real-time metering will be crucial for successful outcomes (Okeke, et al., 2024).

- ➢ *Economic Feasibility and Lifecycle Cost Analysis*

The economic feasibility of integrating PV/T systems with HVAC infrastructure in energy-positive buildings hinges on detailed life-cycle cost analysis, including capital expenditure, operational savings, maintenance, and potential revenue streams from energy export. De Arruda et al. (2023) reveal that solar integration models in building applications can yield positive net present value when system sizing, incentive frameworks and operational profiles are optimized as shown in table 3. In Pennsylvania, financial modelling should account for state and federal tax credits, local net-metering rates, HVAC load offsets (thermal and electrical), and expected system degradation. One practical metric is levelised cost of energy (LCOE) encompassing both electricity and heat yields; when combined with HVAC load reduction, payback periods for PV/T-HVAC systems in temperate zones can fall below 10–12 years assuming favourable incentive structure and proper load matching. Moreover, lifecycle cost modelling must incorporate component replacement cycles (e.g., inverters, pumps, fluids), disposal/recycling costs and inflation considerations elements highlighted in the broader discussion of resilient infrastructure investment by Oyekan et al. (2024).

Beyond payback, the value of surplus exported energy and grid-services participation (e.g., demand response) further enhances the business case. A common residential solar case in Pennsylvania reported payback within 11 years under existing rebates; however, when extending the analysis to hybrid PV/T systems and HVAC load reduction, the incremental investment must be justified by higher combined yield and longer operational lifespan. Critical sensitivity analysis must assess solar resource variability (as discussed in Section 4.1), thermal recovery efficiency in HVAC feed, maintenance burden, and local utility rate dynamics. Ultimately, detailed cost-benefit modelling shows that under current state policies and electricity/thermal cost structures, PV/T-HVAC integration in Pennsylvania can achieve feasible economics and support the energy-positive building target provided system design is optimised, incentive capture is maximised, and operations remain adaptive to long-term performance metrics.

Table 3 Summary of Economic Feasibility and Lifecycle Cost Analysis

Aspect	Core Focus	Technical Highlights	Relevance to Decision-Making
Cost Framework	Evaluation of capital cost, maintenance, and lifecycle savings of PV/T-HVAC integration.	Uses metrics such as LCOE, NPV, and IRR incorporating both electrical and thermal output.	Enables financial justification for hybrid renewable adoption.
Payback and ROI	Payback period of 10–12 years in temperate zones with favorable policy incentives.	Includes impact of state/federal tax credits, net-metering, and HVAC load offset.	Assesses real-world viability of investments in Pennsylvania's policy environment.
Lifecycle Analysis	Examines degradation, replacement cycles, and maintenance requirements.	Incorporates inverter and fluid-system lifespans for accurate cash-flow forecasting.	Ensures sustainable long-term cost-benefit balance for building operators.
Economic Drivers	Incentives, utility tariffs, and grid-service participation enhance project profitability.	Participation in demand response and renewable energy credits boosts ROI.	Provides roadmap for integrating PV/T economics into broader building energy strategies.

V. CHALLENGES, OPPORTUNITIES, AND PERFORMANCE EVALUATION

- ➢ *Technical Barriers in System Integration and Retrofitting*

Retrofitting existing buildings to integrate hybrid photovoltaic-thermal (PV/T) systems presents substantial technical barriers that must be addressed for successful deployment. First, structural and architectural constraints often hamper installation: older buildings may lack sufficient roof load-bearing capacity, face complex building envelope geometries, or include shaded facades that limit optimal PV/T orientation. Bošnjaković et al. (2023) highlight the overlapping responsibilities of façade engineers, HVAC specialists and renewables contractors, noting that lack of multidisciplinary coordination impedes integration of building-integrated photovoltaics (BIPV/BIPV-T) with existing mechanical systems. Moreover, integrated systems require precise matching between electrical generation, thermal recovery, and existing HVAC loops an alignment challenging for legacy control systems and fluid networks.

Second, the retrofitting process must accommodate the coupling of thermal and electrical subsystems, meaning the PV module heat extraction loop must be hydraulically integrated with heat exchangers, storage tanks or air-handler units. Many buildings lack space for such ancillary equipment, and the mismatch between solar harvest timing and HVAC demand typically demands additional controls, bypass valves, and storage buffers. Nair et al. (2022) point to the difficulty of retrofitting advanced energy-efficient technologies in existing stock due to non-standard construction, hidden services and occupant disruption. Furthermore, issues of system commissioning, long-term maintenance and reliability of novel PV/T subsystems (e.g., nanofluid loops, phase-change materials) remain under-explored in retrofit contexts. Collectively, these technical barriers highlight that integration of PV/T with HVAC infrastructure in retrofit scenarios demands early interdisciplinary design, retrofit-specific performance modelling, and dedicated commissioning protocols to ensure safe, high-performance deployment in the built environment (Idoko, et al., 2024).

- *Environmental and Economic Performance Assessment*

A rigorous environmental and economic performance assessment is indispensable for validating the viability of integrating PV/T systems with HVAC infrastructures in energy-positive buildings. From an environmental perspective, integrated PV/T systems reduce both operational carbon emissions (through on-site generation and load offset) and embodied emissions (by replacing standard façade or roof materials). Junedi (2022) undertook a life-cycle assessment (LCA) of integrated PV systems and found payback periods for embodied energy and CO_2 to typically range between 3–6 years in temperate climates as shown in figure 4. However, when the thermal component is added, the complexity increases: the assessment must consider both electrical and heat output streams, variability in solar irradiation, seasonal mismatches, and the degradation of thermal loops over time. Economically, metrics such as Levelised Cost of Energy (LCOE), Net Present Value (NPV), payback time, and internal rate of return (IRR) must account for bundled outputs: electricity fed into the grid, thermal energy supplied to HVAC loops, and avoided HVAC energy imports. Xiaoxiang et al. (2024) note that many retrofit projects under-deliver because performance assumptions did not account for system interaction losses or uncertainty in occupant behaviour. For a Pennsylvania climate, this means dynamic modelling incorporating solar resource variability, HVAC load profiles, and local utility tariffs is critical. Sensitivity analysis should test scenarios including reduced solar yield, increased maintenance, and evolving utility incentive structures. Ultimately, ensuring positive economic and environmental outcomes requires not only high system efficiency but also robust long-term monitoring, accurate baseline definition, and alignment of thermal and electrical value streams in a unified business case.

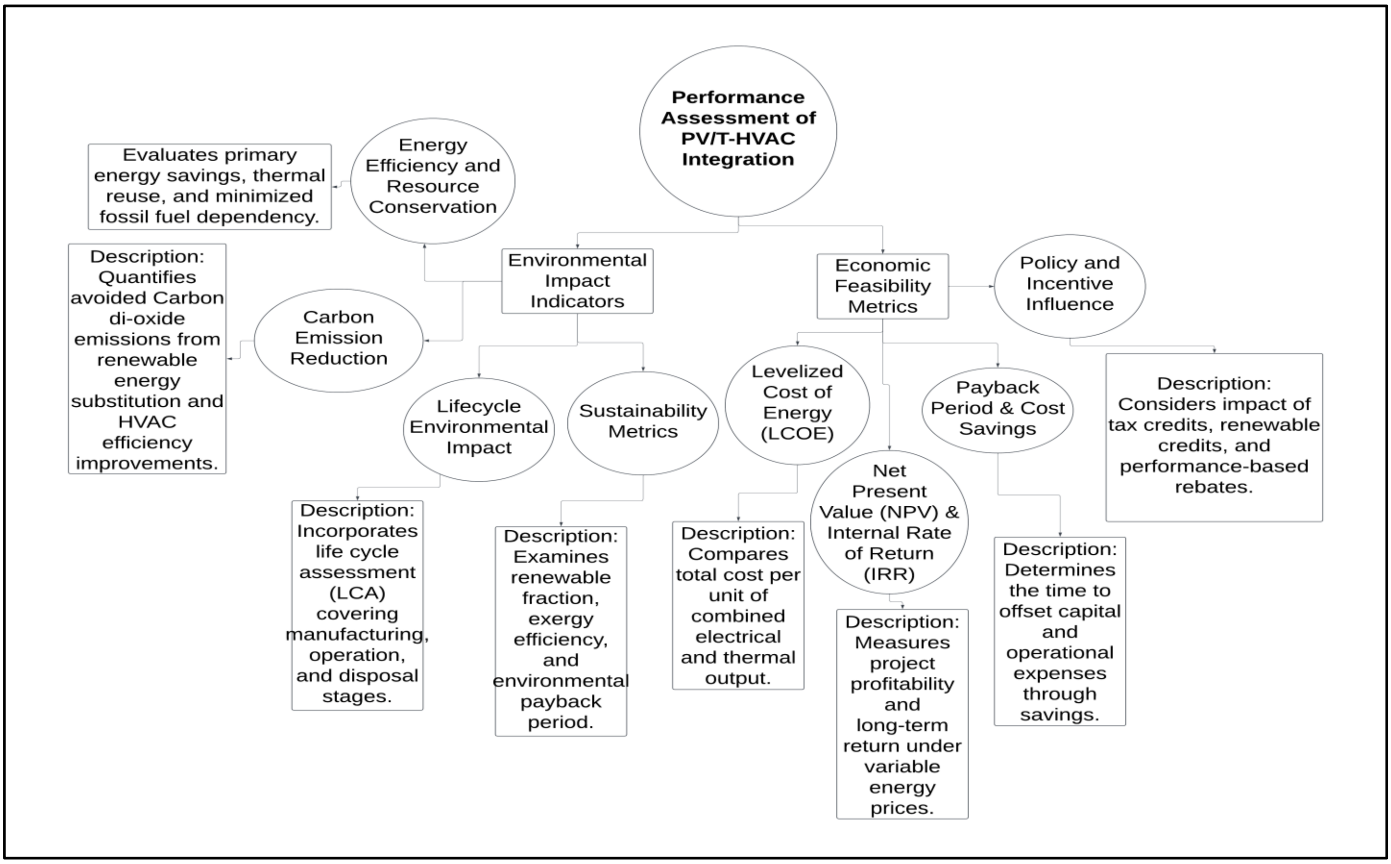

Fig 4 Diagram Illustration of Environmental and Economic Performance Framework for Evaluating PV/T-HVAC Integrated Systems in Energy-Positive Buildings.

Figure 4 illustrates the dual evaluation framework used to measure how photovoltaic-thermal (PV/T) and HVAC integration contributes to sustainable and cost-effective building operations. At its center lies the Performance Assessment of PV/T-HVAC Integration, representing the intersection of environmental sustainability and financial viability. The left branch, labeled *Environmental Impact Indicators*, encompasses metrics that quantify ecological performance. These include carbon emission reduction, which measures the decrease in CO_2 emissions through renewable substitution; energy efficiency and resource conservation, which evaluates reduced fossil fuel consumption and optimized energy reuse; lifecycle environmental impact, accounting for environmental effects across manufacturing, operation, and end-of-life stages through life-cycle assessment (LCA); and sustainability metrics, which track parameters like exergy efficiency, renewable energy fraction, and environmental payback period. Conversely, the right branch, titled *Economic Feasibility Metrics*, captures the financial dimension. It includes the levelized cost of energy (LCOE) for quantifying the cost per unit of useful energy, net present value (NPV) and internal rate of return (IRR) for assessing project profitability, the payback period for capital recovery, and the influence of policy and incentive mechanisms, such as tax credits and renewable rebates, that enhance economic performance. Collectively, the diagram demonstrates that optimal PV/T-HVAC integration must balance environmental gains with economic viability, establishing a synergistic foundation for sustainable, energy-positive building design.

- *Grid Connectivity and Energy Storage Considerations*

Effective connectivity to the electrical grid and integration of energy storage are central considerations when deploying PV/T-HVAC systems in energy-positive buildings. The variability of solar-generated electricity and building thermal demand necessitates buffering strategies to smooth mismatches and enable export or import when appropriate. Amiruddin et al. (2024) demonstrate through system modelling that combining renewables with storage and optimized grid connection significantly reduces grid dependency as shown in table 4. For building-scale PV/T systems in Pennsylvania, this means sizing storage (electrical or thermal) to capture excess generation during midday and dispatch during evening HVAC loads or grid export windows.

Hybrid energy storage systems (HESS) that combine batteries, thermal storage and smart controls offer enhanced operational flexibility. Adeyinka et al. (2024) indicate that hybrid storage offers higher round-trip efficiency and better alignment with variable demand than single-technology systems. In practice, a PV/T-HVAC building system might channel excess PV electricity to charge a lithium-ion battery, while surplus thermal energy is stored in a hot-water tank or phase-change material. During peak HVAC load or grid constraints, the storage can supply heat or electricity, reducing grid imports and enabling possible demand-response participation. However, grid-integration challenges include interconnection agreements, net-metering limits, utility tariffs, and reverse-flow constraints at distribution feeders. These factors must be integrated into system design and cost modelling to ensure seamless connectivity, operational resilience and maximised value from storage-enabled PV/T-HVAC systems.

Table 4 Summary of Grid Connectivity and Energy Storage Considerations

Aspect	**Core Focus**	**Technical Highlights**	**Relevance to Building Resilience**
Grid Integration	Synchronization of PV/T electricity with local grids and HVAC operations.	Smart inverters regulate bidirectional flow; grid constraints considered for safe interconnection.	Improves energy security and grid stability during high-load periods.
Energy Storage Strategy	Deployment of hybrid energy storage (batteries + thermal tanks).	Enhances round-trip efficiency and peak-shaving capabilities.	Balances daytime generation with evening HVAC demand.
Operational Optimization	Predictive algorithms manage charge/discharge cycles.	Prioritizes storage during solar surplus and dispatch during peak HVAC load.	Ensures maximum self-consumption and reduced dependency on grid imports.
Policy & Technical Challenges	Interconnection limits and tariff complexity affect adoption.	Requires clear regulatory frameworks for two-way metering and storage incentives.	Lays groundwork for future smart-grid participation of PV/T-integrated buildings.

- *Stakeholder Perspectives: Architects, Engineers, and Policy Makers*

The success of integrating PV/T systems with HVAC infrastructure in energy-positive buildings hinges significantly on stakeholder alignment among architects, engineers and policy-makers. Architects must incorporate solar harvesting layers and HVAC thermal loops into the building envelope from the conception phase, ensuring placement, tilt, aesthetics and façade integration support both PV generation and HVAC coupling. Engineers, alternatively, must design mechanical and electrical systems that can exploit dual outputs, electricity and heat via fluid loops, storage, and controls, while ensuring occupant comfort and system reliability. Arnaout et al. (2020) found in case-study research that misalignment between design teams, unclear roles and fragmented responsibilities lead to cost overruns and performance gaps in building-integrated PV projects.

From the policy-maker perspective, incentives, building codes and standardised pathways strongly influence adoption. Xiaoxiang et al. (2024) argue that many retrofit projects fail due to insufficient communication, lack of trust between stakeholders and regulatory frameworks lagging technology capabilities. In the Pennsylvania context, policy instruments that incentivise dual-output systems (electrical + thermal) and facilitate integrated design workflows are critical. Building-certification schemes, tariff structures for both heat and electricity export, and standardised commissioning protocols can drive stakeholder collaboration and reduce risk (Gayawan, & Fagbohungbe, 2023). Thus, ensuring that architects prioritise solar-HVAC synergy, engineers implement robust system architecture, and policy-makers align regulatory and financial frameworks creates the ecosystem necessary for mainstream adoption of PV/T-HVAC systems in energy-positive buildings.

VI. FUTURE DIRECTIONS AND CONCLUSION

- *Emerging Trends in AI and Predictive HVAC Optimization*

Artificial intelligence (AI) and machine learning (ML) are redefining the landscape of energy management by enabling predictive control, fault detection, and autonomous HVAC optimization in energy-positive buildings. Predictive HVAC optimization harnesses real-time sensor data, weather forecasts, and occupancy analytics to preemptively adjust system operations for peak efficiency. Algorithms such as reinforcement learning, gradient-boosted regression trees, and neural network-based control models can anticipate fluctuations in thermal load and adjust setpoints dynamically to minimize energy waste. In integrated photovoltaic-thermal (PV/T) systems, AI can predict solar irradiation patterns and adapt HVAC operations to align with the generation curve, ensuring the highest possible utilization of on-site renewable energy. Predictive maintenance models further use anomaly detection and time-series forecasting to identify component degradation in compressors, chillers, and heat exchangers before failure occurs, improving system reliability. For example, AI-driven control strategies can schedule thermal storage charging during midday solar peaks and discharge during evening HVAC demand, achieving grid harmonization and reduced energy costs. As buildings become increasingly interconnected through IoT networks, predictive analytics will enable HVAC systems to operate not merely as mechanical assets but as intelligent, self-optimizing subsystems within an adaptive, renewable-driven energy ecosystem.

- *Potential of Digital Twin and Building Information Modeling (BIM) Integration*

The convergence of Digital Twin (DT) and Building Information Modeling (BIM) technologies offers transformative potential for optimizing PV/T-HVAC integration in energy-positive buildings. A Digital Twin is a dynamic, data-driven virtual replica of a physical system that continuously mirrors its performance using real-time data streams from IoT sensors. When coupled with BIM's geometric, spatial, and material data, DTs can simulate and monitor thermal dynamics, electrical generation, and HVAC interactions in a unified virtual environment. This integration enables engineers to visualize system responses to varying climatic and operational conditions, predict energy consumption patterns, and optimize control strategies before implementation. Digital twins also enhance fault detection by comparing predicted versus actual system performance, facilitating rapid diagnostics and maintenance planning. In practice, a PV/T-HVAC digital twin could simulate the interaction between solar irradiation, thermal fluid loops, and building occupancy to fine-tune operational parameters for maximum efficiency. For retrofits, BIM-DT fusion assists in planning component placement, verifying structural compatibility, and quantifying lifecycle impacts. Furthermore, linking BIM-DT models with energy management platforms supports performance benchmarking and compliance with green building standards. The resulting cyber-physical ecosystem creates a foundation for continuous commissioning, adaptive energy control, and the long-term sustainability of energy-positive infrastructure.

- *Recommendations for Policy and Design Implementation*

To scale the adoption of PV/T-HVAC systems for energy-positive buildings, both design practices and policy frameworks must evolve toward integration, adaptability, and incentivization. Policymakers should establish standards that recognize hybrid renewable systems capable of producing both electrical and thermal energy, ensuring they receive equitable financial incentives and streamlined permitting. Mandating energy modeling during the early design stages will help architects and engineers embed PV/T-HVAC synergy into the building's conceptual framework rather than as a post-construction retrofit. Governments and local authorities should also develop grant mechanisms for digital twin adoption and real-time monitoring systems, promoting data transparency and operational accountability. On the design front, engineers must adopt modular architectures that allow seamless integration between renewable subsystems, HVAC equipment, and smart control platforms. Interdisciplinary collaboration among architects, mechanical engineers, and data scientists should be institutionalized through integrated project delivery (IPD) models. Educational initiatives targeting contractors and facility managers can bridge knowledge gaps in system operation and maintenance. Furthermore, lifecycle-based procurement models and carbon performance disclosure requirements should be embedded into building codes, aligning market incentives with sustainability outcomes. By aligning technical design principles with coherent policy instruments, Pennsylvania and similar regions can accelerate the realization of intelligent, renewable-integrated, energy-positive urban environments.

- ➢ *Conclusion: Toward Scalable Energy-Positive Building Solutions*

The integration of photovoltaic-thermal systems with HVAC infrastructure represents a crucial step toward achieving self-sustaining, energy-positive buildings capable of meeting future energy and environmental challenges. This review underscores that success lies not solely in technological advancement but in systemic convergence linking renewable generation, thermal management, digital analytics, and policy innovation into a cohesive ecosystem. The synergy between PV/T and HVAC systems transforms buildings from static energy consumers into active, adaptive energy producers. Advanced materials such as nanofluids and phase change media, coupled with AI-driven predictive controls and digital twin-enabled diagnostics, create unprecedented opportunities for real-time optimization and resilience. Economic feasibility improves as energy storage, smart grid participation, and long-term savings offset initial investment costs. Yet, scalability requires removing technical barriers in retrofitting, promoting multidisciplinary collaboration, and establishing supportive regulatory frameworks. Pennsylvania's diverse climate and progressive policy landscape provide a fertile ground for demonstrating replicable energy-positive prototypes that balance efficiency, affordability, and occupant comfort. As global urbanization accelerates, scaling these integrated systems from individual buildings to district-wide implementations will define the next frontier of sustainable infrastructure—where architecture, data intelligence, and renewable energy coexist symbiotically to achieve a net-positive built environment.

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