ASHRAE International Building Decarbonization Conference 2024
ASHRAE ASHRAE Spain Chapter

Feasibility Analysis and Evaluation Framework of Integrating Novel PVT with Low-Exergy Systems

Youssef Elomari
Student Member ASHRAE

Giorgos Aspetakis
Student Member ASHRAE

Qian Wang
Fellow ASHRAE

ABSTRACT HEADING

Air-Based PVT utilizes air as a transfer medium to extract heat from the backside of the PV module, where the waste heat can be further recovered and directed to other building energy systems. This study analyzes and maps various integration strategies for air-PVT with low-exergy systems, by examining their feasibilities critically. Engineering, efficiency constraints and other critical factors are considered. Meanwhile, given the engineering features, climate and cost, a thorough evaluation framework is developed. This aims to further assist engineers to effectively select the optimal integration configurations, benchmarking the as-built installations of a given building. This study primarily focuses on five integration strategies that built upon commonly used existing building installations in Scandinavian climate, namely, 1) Preheating the incoming air for frost prevention applications of mechanical ventilation systems with heat recovery: 2) Coupling with Exhaust Air Heat Pump systems for space heating applications; 3) Coupling with thermal-storage or integrating air-source heat pump systems with heating and domestic water supply applications, 4) Encompassing both night sky radiative cooling and daytime desiccant cooling systems applications, and, 5) Integrations with Energy Recovery Ventilation. Moreover, the study explores other potential operations with, e.g., medium to long-term thermal storage applications by considering borehole heat exchangers, latent heat storage from both stand-alone tanks and building envelopes.

INTRODUCTION

Decarbonization of buildings is crucial for the sustainable energy transition and mitigation of the climate crisis. In particular, 40% of building energy usage is attributed to HVAC systems (IEA, 2022). Integration of decentralized renewables can enable the rigorous transition to carbon free built environments, through extended scalability (Zhu et al., 2023). Photovoltaic/Thermal (PVT) collector technology is deemed highly promising, given the dual generation of both electrical and thermal energy. This has been expressed by growing research interest in Building Integrated PVT (BIPVT). Efforts have mainly focused on water based PVTs, yet those present several challenges in integration with the building envelope. This has led investigators to shift the attention to easy-to-install solutions, such as air-based configurations. The field is rather emerging though and emphasis has been given mostly to the component level. Up to the end of 2021 air-based PVT dominated the market having the 45.5% of the installed capacity, surpassing uncovered water PVT collectors sitting on 44.2%. Figure 1a shows systems installed worldwide according to collector type or application (Weiss & Spörk-Dür, 2022). An abrupt shift in 2022 led to air-PVT collectors disappeared entirely from the market and uncovered PVT collectors rose to 87%. This was mainly due to changes in funding programs in France. Figure 1b presents the difference between 2021 and 2022 (Weiss & Spörk-Dür, 2023).

It can be found that applications of the technology are significantly varied and scattered among different fields. Therefore, the aim of this study is to map the realized and possible implementations of Air-Based PVT integration to building energy systems and give feasibility estimations for different integration strategies with building HVAC systems that have been commonly used. In the end, a configuration combining heat recovery exhaust flow, Air-Source Heat Pump (ASHP) and PVT air flow is presented.

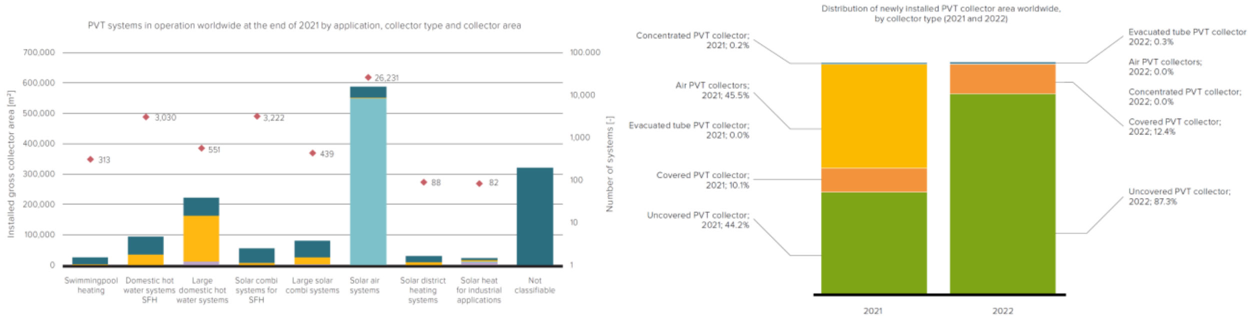

Figure 1 (a) PVT system in operation worldwide by application, type, area at the end of 2021 and (b) Distribution of newly installed PVT collector area worldwide by collector type in 2021 and 2022.

LANDSCAPES OF THE EXISTING INTEGRATION STRATEGIES

Up to now, a major part of air-based PVT studies has been concentrating on component design rather than the effective integration into building energy systems, or other equally significant domains, such as monitoring, control, etc. Despite the numerous reported solar air heating installations, full-scale monitored applications were significantly few, with most studies being of numerical analysis. As a general rule of thumb, for air-based PVT and building energy system integrations, it is reported that temperature rises were in the range of 5-20 °C and efficiencies of 20-50%, as reviewed by (Rounis et al., 2021).

Fresh Air Preheating/Direct Space Heating

Fresh air preheating refers to the preconditioning of the required ventilation air before entering the built environments, commonly before treatment from the air handling units. Supplying the PVT heated air to the condioned room is designated as direct space heating. Space heating and ventilation are energy intensive and contribute greatly to the overall energy usage of buildings. Studies have found that pumping the heated airflow directly to conditioned is not ideal, since the airflow temperature is commonly lower that that of the thermal zone (e.g., 20 °C), particularly in cold climates. It might be feasible in areas with mild winters and can be favored due to its relative simple installation. (Bambara, 2012) examined a configuration of Unglazed Transpired BIPVT system under real conditions in Canada, where it was found that the system worked best when it was close to the mechanical room and with correct positioning of ductwork. This setup was able to meet about 33% of the heating needs of ventilation systems by preheating incoming air. Table 1 describes full scale installations with representative configurations.

Table 1. Full Scale Installations

Reference	Output Temperature or Rise	Remarks
GSE Air system (Ramschak & others, 2020)	17-57 °C	30% energy demand, Solar Fraction = 43%
(Bot et al., 2021)	ΔT = 6-14 °C	Data for one year
Sunovate Domestic Pilot (Ramschak & others, 2020)	-	Closed air loop for space heating
(Athienitis et al., 2011)	-	75 kW peak
(Bambara, 2012)	Up to 20 °C and ΔT = 12 °C	Annual generation: 55 MWh thermal, 20 MWh electrical

Heat Recovery

Different ways of connecting the airflow of PVTs with Heat Recovery Ventilation (HRV) systems have been proposed. One way is to preheat the outdoor air that is supplied. The utilization of heated air from the PVT collector can help with resolving freezing and dew condensation issues that arise with traditional HRV systems, caused by low ambient winter temperatures in cold climates countries such as Sweden. Frost formation in heat recovery exchangers like plate heat exchangers and energy wheels can occur when the temperature drops below -5 °C and -12 °C, respectively *[Ref]*. (Ahn et al., 2015) carried out an experimental study to explore how the waste heat recovered from PVT could be utilized in HRV systems to preheat incoming outdoor air. The findings revealed that utilizing preheated air from PVT enhanced the heat transfer efficiency by 20%. However, an additional amount of dampers and connecting ductwork was required. An example is shown in Figure 2.

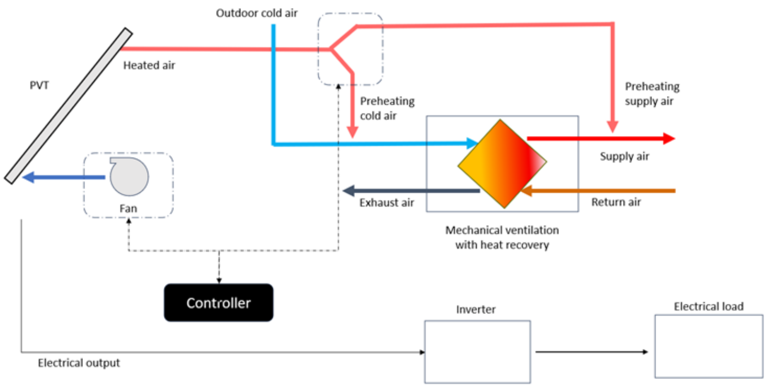

Figure 2 Example of PVT integration with HRV.

Heat Pump

Air handling units or the outdoor units of the ASHP require typically high volume flows, which a PVT system might not be able to supply exclusively on its own. A combination of exhaust air from the building or ambient air and preheated air from the PVT collector is suggested to meet the required airflow rate. (R. S. Kamel & Fung, 2014) simulated the use of BIPVT with ASHP in a cold climate using TRNSYS. Their study concluded that using BIPVT for preheating the flow to the evaporator led to a saving of $500 in annual electricity bills and a reduction of 1734.7 kg CO2 in greenhouse gas emissions. (Saini et al., 2021) employed an Unglazed Transpired Solar Collectors (UTSC) to increase the temperature of the inlet air on the evaporator side of the ASHP. The results showed that the integration of UTSCs has a small, yet positive impact on the overall system performance. However, researchers have ignored the defrosting effect that UTSCs have in this process, and it has rarely been analyzed. (R. Kamel et al., 2015) presented a configuration that involved BIPVT, ASHP, and Thermal Energy Storage (TES). The TES (concrete slab or gravel bed beneath the floor) stored heat recovered from the BIPVT during the day and released it at night to enhance the heat pump's performance. This improved the heat pump's Coefficient of Performance (COP) from 2.74 to a maximum value of 3.45. Additionally, the configuration reduced electricity consumption by 20% during winter. It was additionally noted that managing this combined system under various weather conditions was challenging, especially connecting the ducting work from the BIPVT to the HP, which required advanced engineering. To solve this, a specially designed louver box with dampers was introduced, allowing airflow to be directed differently depending on the control strategy used. An air-type PVT system connected to an air-to-air heat pump was presented by (Barone et al., 2019). The system was examined in a range of European climate conditions and showed the efficiency evaluating the main energy savings (11.0 - 19.7 MWh/year, or 52 - 80%), saved CO_2 emissions (4.64 - 10.4 tCO_2/year), as well as highly acceptable payback period (3.2 - 4.8 years). The concept of combining exhaust and PVT flows is presented in Figure 3.

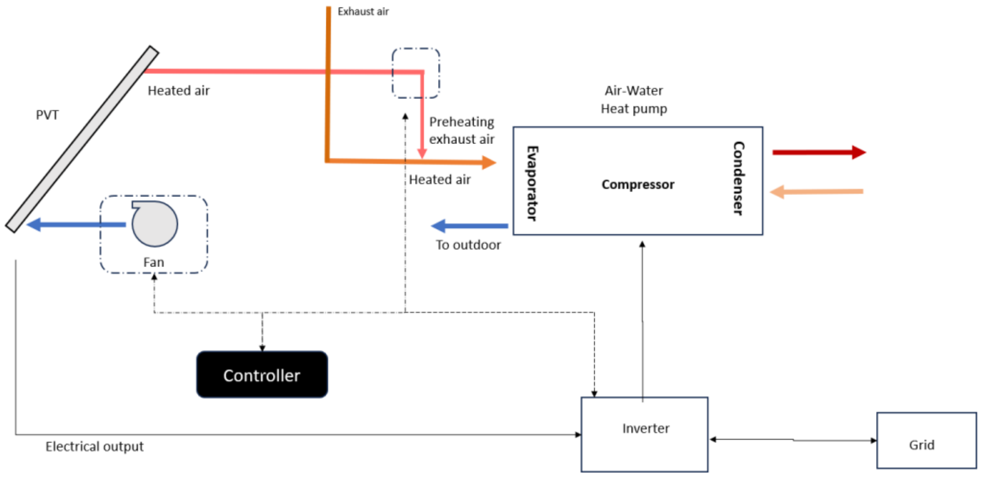

Figure 3 ASHP utilizing as a source for the evaporator the mix of PVT heated air and ventilation exhaust air.

Solar Cooling

Solar thermal cooling is steadily gaining attraction. Cooling demand is increasing rapidly and solar thermal generation coincides with peak cooling demand. Absorption and adsorption chiller technology have been primarily investigated in solar applications. For air-based PVT, desiccant cooling can be used. Desiccant wheels cool humid air streams by absorbing humidity but need to be regenerated using heat for continuous operation. (Guo et al., 2017) described in their review the potential of utilizing PVT for solar cooling applications, specifically desiccant cooling and dehumidification. Their analysis indicated that the temperature level requirements for low temperature desiccant cooling can be met by PVT generated thermal output. Methods for further decreasing the temperature restriction were proposed. In an extensive study of a desiccant cooling system with combined PVT and solar air collector field equipped with heat pipes, (Fan et al., 2019) simulated and analyzed its operation. The aim was to study the dynamic interactions between conditioned space and the cooling system while also optimizing parameters related to sizing and control. The component has been validated in a previous study, yet the whole system interaction has not, as noted by the authors. The simulation still highlights the potential, showcasing solar fraction up to 96%. Desiccant regeneration temperatures of studies reviewed by (Ren et al., 2018) are in the range of 35-120 °C with a significant portion noting that acceptable efficiencies for dehumidification can be achieved in the 60-70 °C range.

THERMAL ENERGY STORAGE INTEGRATION

Sensible Storage

Heat transfer from a heated airflow to a sensible storage tank is not optimal and has naturally led researchers to almost exclusively pair water tanks with water-based PVT, or certain other refrigerants in closed loops. The concept should not be discarded completely though given the fact that the inherent benefits of air-based installations for residential integration can potentially outweigh the relatively poorer heat transfer performance. This is particularly applicable to water tank combinations with air-to-water heat pumps, where space heating and Domestic Hot Water (DHW) production can be assisted by PVT generation. The other method consists of placing an air-to-water heat exchanger in the system, with relative lower efficiency compared to water based systems. Such a configuration was demonstrated in the “Deep Performance Dwelling” building that competed in a Solar Decathlon competition. Installation and modelling of operation was detailed by (Rounis et al., 2018). For the heating season, heated airflow of up to 30 °C generated in the air-based building integrated PVT system is directed through an air-to-water heat exchanger stored to the cold tank of a binary tank heat pump combined system. Yet even on this front progress is being made with more efficient heat exchangers being developed.

Phase Change Materials

Latent thermal storage solutions utilizing Phase Change Materials (PCM) have dominated in solar energy storage investigative efforts the past decade. PCM storage offers space savings and longer cycles. Similarly to other storage solutions, full-scale applications utilizing PCM are hard to come by, where studies almost exclusively deal with component level analyses. (Fiorentini, Cooper, & Ma, 2015) detail in their investigation the installation and operation of an air-based PVT coupled with PCM thermal storage. The system operated in cooling mode, but the same layout may be utilized for the heating season. The PVT direct cooling supplied 30.7 kWh with COP of 6.2 and the PCM discharging 5.6 kWh with COP of 2.7 for a period of 48 hours. An illustration of the system is presented in Fig. 4. PCM are generally considered costlier solutions than other forms of storage. The melting point can be determined in the beginning by the correct mixture of PCM but that cannot be altered at a later stage. Thus, systems designers need to take into consideration the melting point of the material which can limit their flexibility, given that solar energy is intermittent, with varying temperature levels of heated airflows. When physical space is a factor, PCM are ideal due to their higher energy density than water tanks, offering smaller spatial footprint for the same amount of storage capacity than for example water tanks offer. As a general rule, (Asefi et al., 2021) determine for building integrated PVT systems, the melting temperature should not exceed thermal comfort levels (20–22 °C). For hot climates with average ambient air temperatures higher than 30 °C different implementations are deemed appropriate.

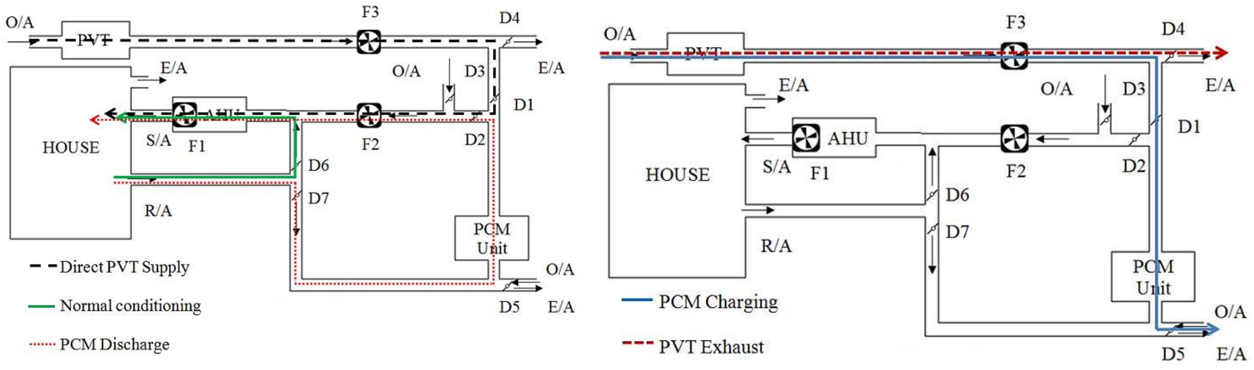

Figure 4 (a) Layout showcasing direct PVT heating and PCM discharge operation (b) PCM Charging and exhaust into ambient operation. (Fiorentini, Cooper, Ma, et al., 2015). Under CC BY-NC-ND 4.0 license.

Thermal Mass of Building

Storage alternatives are limited concerning heated air and remain costly or difficult to install. A potential strategy for storing this form might utilize the building structure itself, specifically, their thermal mass. It can be described as the inertia of built environments to temperature fluctuations and depends on the materials used. Passively, building parts absorb, store and release thermal energy. (Chen et al., 2010) monitored the performance of a BIPVT and Ventilated Concrete Slab system in a demonstration building during heating season. The passive storage displayed small temperature variation but given its large capacity was able to significantly influence the temperature of the living space, sustaining the level above setpoint until late night, achieving savings in heating. The technique can potentially be fitting for renovation projects where minimal intervention is required. Another application might involve combating moisture problems which historical buildings suffer from. Pumping heated air into basements or under floors might mitigate these effects. In the case of new buildings, hollow concrete floor slabs, available in the market, provide efficient heat transfer solutions.

Packed Bed Storage

Packed beds are a type of sensible storage where thermal energy is transferred to enclosures of solid particles, increasing their temperature. Materials can range from stone pebbles to steel industry byproducts. The enclosure is typically created by excavating the ground. (Almendros-Ibáñez et al., 2019) summarized solar thermal applications combined with packed bed storage, a technology that has been investigated and documented starting already in the 1970s with different materials and arrangements. PVT systems designs can potentially operate at the lower range of temperatures (<100 °C) just as efficiently. Findings pointed out that stratified beds were suitable for low temperature solar applications and high solar fractions were reported for space heating and DHW production demonstrations. (Pantic et al., 2010) demonstrated the operation of BIPVT that charged a rock bed storage unit during the day. Heat recovered from the bed resulted in the reduction of the heat load by 48.5% and an average increase of temperature of 2.5 °C compared to a regular zone.

OTHER INTEGRTION STRATEGIES?

Nighttime Radiative Cooling

In addressing the issue of solar thermal energy's temporal mismatch between the availability and demand, notably during summer months, while the abundance of solar thermal energy generation, the demand for heating is low. On the other hand, there is a high demand for cooling. Solar cooling, especially when integrated with air-based PVT alongside desiccant cooling technology, presents itself as a promising solution to this seasonal energy mismatch. Air-based PVT face the limitation of inactivity during nighttime due to the absence of sunlight. To overcome this limitation, a novel integration is proposed in order to extend the total operation: utilizing the night sky radiative cooling effect of PVT collectors as an extended mode within a solar desiccant cooling system. Night sky radiative cooling is the technique of utilizing outer space as a temperature sink through radiation and can augment space cooling (Eicker & Dalibard, 2011). Combining this with desiccant cooling allows the operation of two modes, during the daytime, using the wase heat from the air type PVT collectors as heat reactivation air for the desiccant cooling and nighttime radiative cooling, seen in Figure 5.

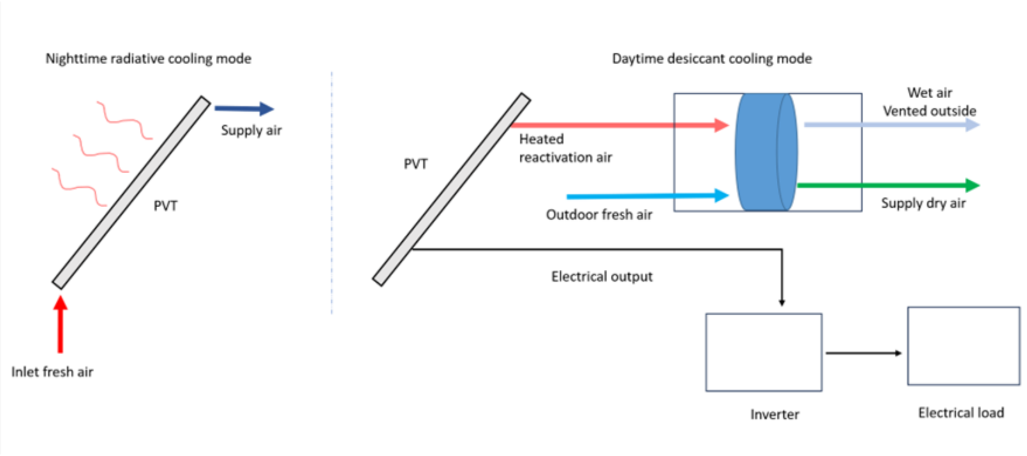

Figure 5 Extension of cooling capability through combined operation of desiccant and nighttime radiative cooling.

Borehole Regeneration

Summertime applications might be limited in regions with no cooling loads. Utilizing warm airflows in other forms than DHW preparation or solar cooling lead to extended operation throughout the year. Thus, seasonal performance is enhanced and renders PVT an attractive energy solution for buildings with no cooling needs. The regeneration of boreholes has been investigated due to the thermal degradation of the soil caused by ground source heat pump systems (Wallin, 2021). Several methods have been proposed, including solar thermal collectors, wastewater heat utilization and exhaust ventilation flows. Specifically, the latter was investigated by (Wallin, 2021) who analyzed a system where though the use of an air-to-water heat exchanger, exhaust ventilation air regenerated boreholes. It was noted that for Nordic climates, the combination resulted in shallower borefields, enabling geothermal systems in densely built areas. Waste air utilization performed better in high energy demand borehole fields rather than high peak heat demand and the levelized cost of heating for waste was reported lower than wastewater heat. PVT generated airflows could potentially replace or boost the waste air supply. Systems with water-based PVT have investigated various configurations (You et al., 2021), achieving emission reduction of up to 63% (Chhugani et al., 2023), but air-based solutions are lacking. Future investigations could include such scenarios for complementing the summertime operation of PVT configurations.

GUIDELINES

Integration of air-based PVT generation to the energy systems of buildings has therefore multiple alternatives. In Figure 6, a condensed landscape summary is presented to enhance the clarity of the ideas put forward. Green arrows signify the potential synergy between different methods. Table 2 lists attributes of the integrations deemed significant by the authors. The aim is to present a complete layout of possible integration strategies, tested or not, to researcers, engineers and designers wishing to incorporate air-based PVT systems in their projects.

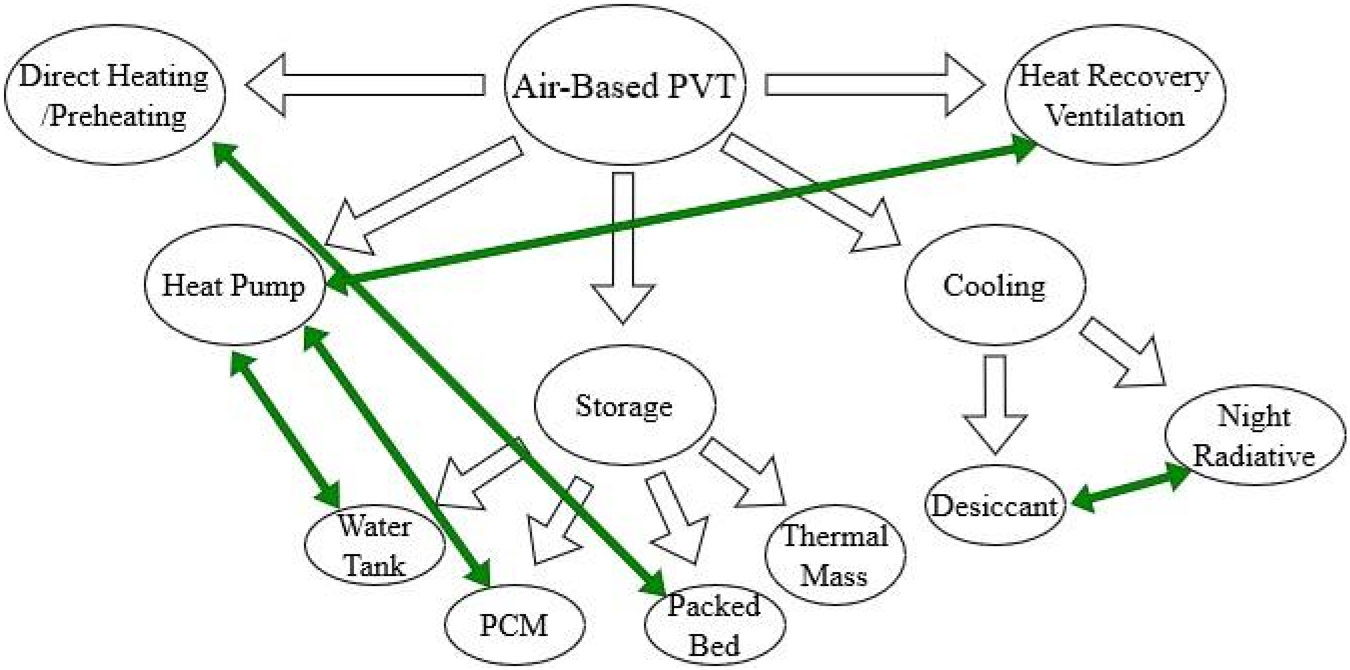

Figure 6 Mapping of possible integration scenarios of air-based PVT to building energy systems.

Table 2. Summarized Remarks of Integration Strategies

Integration	Merits	Deficiencies

Direct Heating/Preheating	Simplicity, Easy Installation	Not suitable for cold climates
Heat Recovery Ventilation	Defrosting of HRV	Possible reduction of HRV efficiency
Heat Pump	Wide applications, Reliable	Installation Difficulties
Desiccant Cooling	Match of demand and supply	Costly, complicated setup
Radiative Cooling	Extend cooling operation	Standalone operation challenging
Water Tank	Affordable, wide application, easy	High volume requirement, air-to-water HX
PCM	Low volume, High Capacity	Costly, Complex, Degradation
Packed Bed	Affordable	Low efficiency
Building Thermal Mass	Low intervention, High capacity	Thermal Losses
Borehole Regeneration	Summer Operation, Shallower Field	Air-to-water HX, no direct effect

CONCLUSION

This study performed a feasibility analysis, focusing on air-based PVT integration strategies with building energy systems. The following conclusions are drawn:

- Overall, a significant lack of installations and demonstrations is noted. However, investigations point to multiple integration capabilities of Air-based PVT.
- Integrating PVT with exhaust air heat pump for heating and desiccant cooling operating at low dehumidification temperatures, e.g., 50-70 °C, display strong potential.
- Despite the current market and technical challenges, it is clear that air-based PVT systems can assist in reducing the both overall energy usage of buildings and provide decentralized solutions with storage system integrations. However, full scale implementations are needed for greater dissemination. Progressing this technology could be pivotal in promoting sustainable and energy-efficient building solutions of the future.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from the Swedish Energy Agency (grant number: 52488-1).

NOMENCLATURE

ASHP = Air Source Heat Pump
BIPVT = Building Integrated PVT
COP = Coefficient of Performance
DHW = Domestic Hot Water
HRV = Heat Recovery Ventilation
PCM = Phase Change Material
UTSC = Unglazed Transpired Solar Collectors

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