ARTICLE IN PRESS
JID: ENBENV [m5GeSdc;October 14, 2023;16:3]

Energy and Built Environment xxx (xxxx) xxx

Contents lists available at ScienceDirect

Energy and Built Environment

journal homepage: http://www.keaipublishing.com/en/journals/energy-and-built-environment/

Review

Critical review of Air-Based PVT technology and its integration to building energy systems

Giorgos Aspetakis[a,*], Qian Wang[a,b]

[a] Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, Teknikringen 78, Stockholm, 114 28, Sweden
[b] Uponor AB, Hackstavägen 1, Västerås, 721 32, Sweden

ARTICLE INFO

Keywords:
Building integration
RES
PVT
Air-Based

ABSTRACT

Climate crisis mitigation roadmaps, policies and directives have increasingly declared that a key element for the facilitation of sustainable urban development is on-site decentralized renewable energy generation. A technology with enhanced capabilities, able of promoting the integration of renewable energy into buildings, for energy independent and resilient communities, is Photovoltaic Thermal (PVT) systems. Ongoing research has potential yet displays a lack in unified methodology. This limits its influence on future decision-making in building and city planning levels. In this investigation, the often overlooked air-based PVT technology is put on the spotlight and their suitability for integration with energy systems of buildings is assessed. The aim of this study is to highlight vital performance and integration roadblocks in PVT research and offer suggestions for overcoming them. The methodology of reviewed literature is examined in detail with the goal of contributing to a unified approach for more impactful research.

1. Introduction

The decarbonisation of the building sector shall play a vital role in combating the ongoing climate crisis. Buildings contribute already massively to the total greenhouse emissions, up to 33% globally [1]. In the meantime, the European Union's existing buildings are outdated and require renovation. It is projected that approximately 85–95% of the current building stock will still be in use by 2050 [2]. It is imperative to retrofit these structures in order to achieve the EU's objective of attaining climate neutrality. One of the main pillars of this 'renovation wave' is the decarbonisation of heating and cooling. To combat this challenge, low-carbon roadmaps like the EU Green Deal and Built4People have been initiated, in order to promote sustainable development practices internationally. Examples include the European Commission energy directive, which states that all new buildings must fulfill Zero Emission Building requirements, starting as of 2030 [3]. Other policies involve the accelerated development of Positive Energy Districts. Urban areas designated as PEDs, aim to generate a surplus of energy other than just covering their demand, by combining renewable energy sources, building energy efficiency and smart technologies.

Another partnership, the Urban Agenda for the EU brings together the European Commission, Member States, cities, and other stakeholders with the aim of improving the quality of life in urban spaces and guaranteeing sustainability, resilience, and inclusivity. One of the main points the agenda has prioritized is energy transition on the local level.

Initiatives like the Covenant of Mayors for Climate and Energy attempt to assist cities in the EU fulfil energy and climate objectives. Commitments typically include the increase of on-site renewable energy generation.

Renewable, on-site energy source integration is therefore set to facilitate the decarbonisation of building energy systems. Solar energy technologies like Building Integrated Photovoltaics and Photovoltaic Thermal collectors are anticipated to have a substantial impact on the transition to green low carbon building environments, due to their decentralised nature and scalability [4].

Sweden, although characterized as prominent in energy transition and in implementing a low-carbon economy, is still marked by significantly high energy use in buildings. An attempt to reinvigorate the renovation of energy inefficient building stock has not delivered satisfying results yet [5]. This could potentially be addressed by developing emerging technologies able to cover the needs of building, in terms of both thermal and electrical energy. Photovoltaic Thermal systems are able to generate renewable, thermal and electrical energy locally, covering the buildings energy needs in a fossil-free manner. Their successful dissemination faces challenges and hence a comprehensive next-step assessment is needed.

1.1. Background

Photovoltaic technology generates energy from incident solar radiation. However only a fraction, typically reaching 25%, is converted into

---

* Corresponding author.
E-mail address: gfasp@kth.se (G. Aspetakis).

https://doi.org/10.1016/j.enbenv.2023.10.001
Received 4 July 2023; Received in revised form 12 September 2023; Accepted 2 October 2023
Available online xxx

Please cite this article as: G. Aspetakis and Q. Wang, Critical review of air-Based PVT technology and its integration to building energy systems, Energy and Built Environment, https://doi.org/10.1016/j.enbenv.2023.10.001

Nomenclature

Nomenclature	Symbols
AHU	Air Handling Unit
BIPVT	Building integrated PVT
CFD	Computational Fluid Dynamics
HP	Heat Pump
HRV	Heat Recovery Ventilation
HVAC	Heating, Ventilation, Air Conditioning
KPI	Key Performance Indicator
LTH	Low Temperature Heating
PCM	Phase Change Material
PV	Photovoltaic
PVT	Photovoltaic Thermal
SAH	Solar Air Heater
TEF	Thermal Enhancement Factor
VG	Vortex Generator
η_e	Electrical efficiency
η_{th}	Thermal efficiency
ρ	Density (kg/m^3)
A	Area (m^2)
f	Friction factor
G	Radiation Intensity (W/m^2)
I_{sc}	Short Circuit Current
$\dot{m}$	Mass flow rate (kg/s)
Nu	Nusselt number
C_p	Heat Capacity under steady pressure
P	Power (W)
T	Temperature (K)
V_{oc}	Open Circuit Voltage

electrical output. This fraction, called efficiency of the photovoltaic (PV) cell, exhibits a inverse relationship with their operating temperatures. The energy not converted into electricity is transmitted back in the form of radiation to the surroundings or dissipated as thermal energy, which inevitably causes a temperature elevation of the PV materials. Higher temperatures introduce electrical resistance losses among other faults, with such efficiency drop rates varying according to the form and material of the cells [6,7]. The result is a reduction of the operating voltage, which further decreases the power output (area of I-V curve), as seen in Fig. 1. This leads to a linear drop in efficiency of up to 0.5%/° C [8–10]. Fig. 2 shows the drop of efficiency with temperature as demonstrated by Nishioka et al. [11]. Moreover, the overall lifecycle is affected negatively by exposure to extended periods of elevated temperature through the degradation the photovoltaic cells [12].

It has therefore been a primary objective of recent studies to reduce the PV operating temperature and maintain it to stable and acceptable levels. Several techniques for cooling PV of have been developed for that matter, as noted by Siecker et al. [13], and more particularly the concept of PVT collectors [14–17]. In essence PVT configurations attempt to prevent material deterioration that would eventually lead to a reduction in durability and efficiency.

Configuring the efficient transfer of waste heat from PV cells, by means of a coolant, allows for the synchronous generation of electrical and power in one system. The synergy of said systems with buildings is gathering attention lately, since the decentralized onsite renewable nature of PVT aligns well with the attempts of decarbonising the building sector. This synergy can be facilitated by Building Integrated Photovoltaic Thermal (BIPVT) technology along with its regular counterpart. BIPVTs are part of the building in terms of structure and aesthetics instead of merely being attached to it. To implement the energy utilization, BIPVT systems can be integrated with low temperature heating systems, such as existing heating and ventilation installations running on low-temperature level. Other integration possibilities are listed in this review, like usage of heat pumps or storing energy for later use.

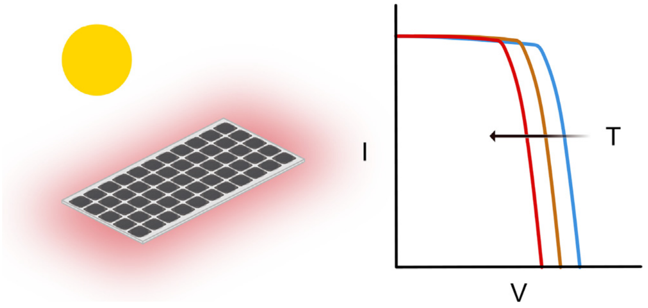


Fig. 1. Efficiency Drop as observed in the I-V curve of PVs.

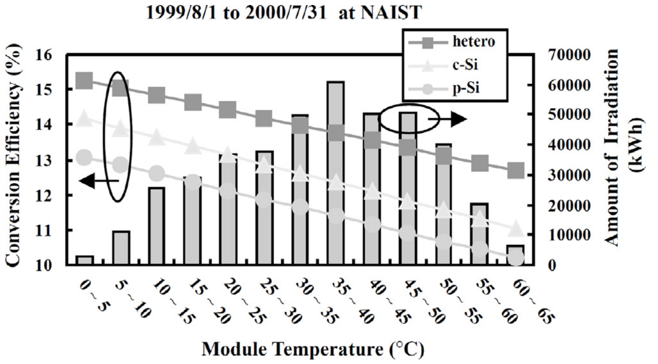


Fig. 2. PV conversion efficiency and amount of irradiation as a function of the module temperature [11]. Reused under Elsevier license number 5615850964301.

1.2. Previous reviews and contribution

Advancements regarding PVT technology and its relationship with buildings have been assessed [18,19]. The reviewed literature tended to focus on theoretical studies highly specific to each case. Additionally, the performance aspect drew most attention [20,21]. A detailed technical review highlighting crucial limitations in Air-Based PVT and its integration to energy systems is missing. The current study aims to combat the specific knowledge gap and lack of systematic testing and provide strategies for accelerating large scale, future-proof implementation. Based on those insights, solutions are pinpointed with the ultimate endgoal of enabling PVT dissemination.

Multiple types of PVT are being researched, as indicated in the referenced reviews. Significant focus has been given to water based systems, above all other forms, due to its its thermodynamic properties and availability. It is however, the authors' conviction that Air based variants are more apt for implementation in buildings. Crucial factors that justify Air based system usage over Water based systems in specifically in building focused applications include [17,22,23]:

- No damaging leakage
- No freezing/fouling
- No electrical hazard

All in all, a capacity for less complex integration. Designers would feel more confident incorporating air flows inside façades or roofs rather than large amounts of water. Other forms, like nanofluids etc. present certain limitations, mostly in terms of viability and cost and are therefore not considered appropriate for implementation yet. Chandrasekar et al. [22] illustrate in their review the potential of different PVT concepts with indicators ranging from effectiveness, reliability, commercialization to complexity, power demand and capital required. Air based

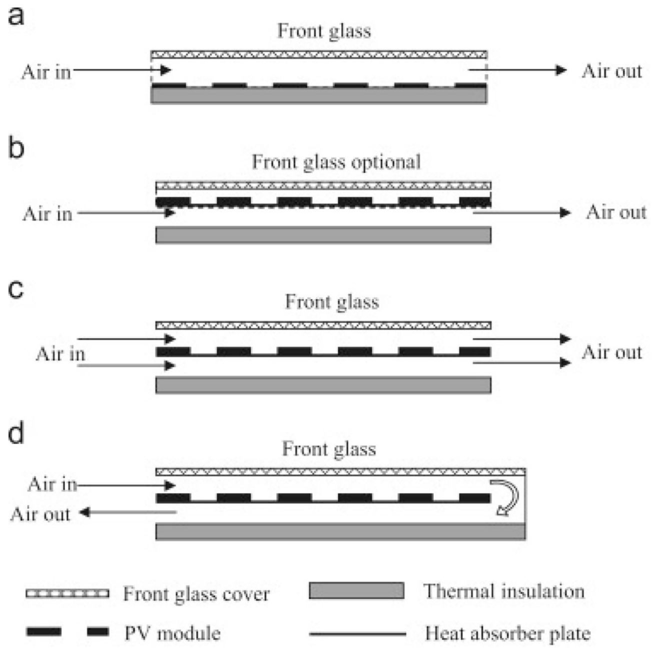


Fig. 3. Typical Air-Based PVT layouts illustrated by Hussain et al. [24], reuse with Elsevier license number 5615281421204.

PVT and the BIPVT concept display improved capabilities. Typical layouts of Air-Based PVT are shown in Fig. 3.

In one of the very few reviews investigating solely air-based systems, Rounis et al. [25] claim that given the simpler design and reduced maintenance needs, they appear to be more suited for building integration than their water-based counterparts. However, in spite of the strong potential that has been exhibited, the technology has not disseminated completely until now and efforts to address this issue have yet to be seen. Air-based PVT technology has been somewhat neglected in favor of the water-based variant. It is this gap in literature that this paper intends to tackle, by identifying the technical challenges in operation and integration that hinder progress. Thus, the present technical review focuses on Air-based PVT systems and Building Integrated applications. To complement these insights, solution from different aspects are proposed.

It is important to note that the current study analyses the operation and integration of such systems from an energy viewpoint. The architectural and structural aspects among others, equally as important, are not investigated here.

1.3. Structure of paper

- Section 2 outlines the state-of-the-art for air based PVT research and and its integration to energy systems, focusing on the roadblocks faced and limitations detected. A detailed account of three main categories is presented.
- Section 3 contains suggested counter solutions and strategies, in response to the deficiencies highlighted.
- Section 4 gives a final summary, listing key points of the study.

2. Challenges

This study focuses on three key technical challenges for air-based PVT, as explained in Section 1. The limitations presented have been classified into three main categories: Performance, Methodology of Experiments and Integration to Energy systems.

2.1. Performance

PVT research mostly focused on methods of enhancing collector performance, that would lead to more efficient and viable systems. Cooling approaches ranged from installing heat flow enhancements like fins to Phase Change Materials (PCM) padding. A selection of parameters influencing BIPV operation was compiled by Asefi et al. [26]. In particular, the operation BIPVT configurations were difficult to adequately assess, as observed by Chow et al. [27]. The process of evaluating heat transfer coefficients is complex, since the effect of multiple variables is present, for example the turbulent or laminar flow in channels, entrance effects, wind loads. The heat transfer of transparent BIPVT system needs to be investigated further. The nature of connecting individual panels in a network were evaluated by Agrawal and Tiwari [28]. In this instance, serial connected configurations directly link the outlet of each collector to the inlet of the next collector. For systems connected in parallel, the final flow is the combination of individual collector flows. A mass flowrate that is constant was deemed suitable for parallel connection, while serial configurations favor constant velocity. Thermal inserts were added to different applications with the aim of augmenting the heat transfer from PV surfaces to the coolant [24,29,30].

Twisted tape inserts in a BIPVT configuration were examined numerically by Benzarti et al. [31]. Findings showed that average surface temperature dropped but hot spots were occasionally created, leading to cell damage. Kumar et al. [32] examined mathematically the operation of a double pass PVT collector with fins attached. Their effect on the efficiency on the thermal and electrical level among other parameters were studied. The model is however very case specific and lacked validation, limiting its impact. Barone et al. [33] utilized hexagonal air ducts to extract heat generated by PV panels. Data was collected from a two month period, May to June, corresponding to a representative summer conditions, according to the authors. The test was used to calibrate a simulation model in which different weather zones and economic strategies were examined. It was noted that when serially linked, the cooling becomes negligible after a number of panels.

The type of PV cell determines the performance of PVT as well. In their analysis, Sharma et al. [34] compared opaque and semi-transparent modules and concluded that the former display higher electrical and exergy efficiency while the latter was beneficial for thermal efficiency.

To further increase the heat transfer in a BIPVT collector, Nghana et al. [35] studied the effect of ribs, particularly their shape, height and pitch, added to the backplate of the setup, shown in Fig. 4. In the end, with right set of parameters and compatible massflow, a reduction of the surface temperature led to an increase of 11.3% in electrical efficiency compared to a smooth channel, while lowering the heat gains through the building envelope by 45.2%.

Kim et al. [36] developed a novel BIPVT configuration utilizing a perforated thermal plate for augmented heat transfer to the airflow, illustrated in Fig. 5. Experimentation was performed indoors and outdoors, with respective results compared in order to gain insights regarding the testing procedures. The authors highlighted the difficulty of this process, notably the particular considerations that need to be accounted. Nevertheless, the same trends regarding the thermal efficiency dependence on mass flow were observed in both cases. Issues like this with the testing of PVT and BIPVT are commonplace and are described in more detail in the next section focusing on the methodology of cited research.

To summarize, available literature attempted to boost the heat transfer taking place in numerous PVT configurations, mainly through the modification of the cooling channel, addition of fin structures or the utilization of novel materials.

2.2. Methodology

A general discrepancy in regards to scientific methodology can be detected in numerical and experimental PVT/BIPVT studies. For simu-

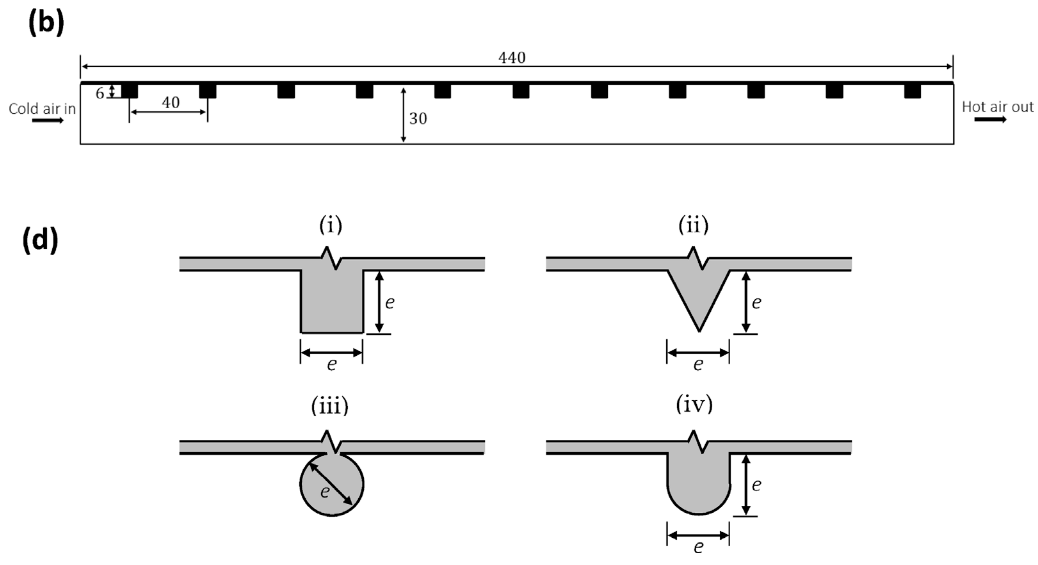
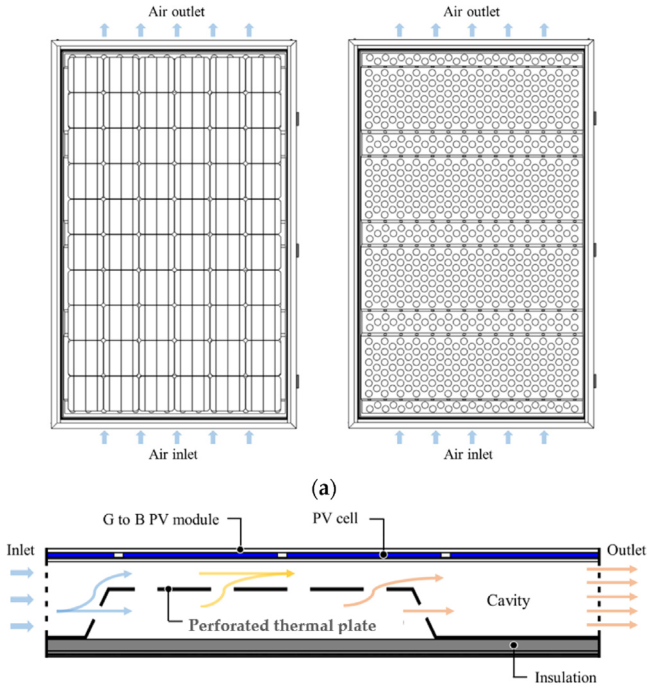


Fig. 4. Rib designs by Nghana et al. [35].



(a)

(b)

Fig. 5. Perforated thermal plate design by Kim et al. [36].

lations, differences in problem definition, governing equations, boundary conditions, software packages etc. can lead to dissimilar findings. Rounis et al. [25] detected that there is disparity in the literature regarding the process of measuring performance. Furthermore, the lack of standardized and comparable designs was noted. With the goal of initiating a discussion around this topic, a basic outline for standardized testing was presented. The present review aims to continue this discussion, with short state-of the-art for the various categories and stages of testing and measuring. These shall include points which are considered lacking, from the perspective of procedure, equipment or methodology in simulation, field and laboratory environments.

Table 1
Categorization of Simulation Methods.

Category	Software
Thermal nodal network	Custom
Variations of the Hottel-Whillier model	Custom
System analysis w/ energy simulation software	TRNSYS EnergyPlus ESP-r Energy-10
Computational Fluid Dynamics for performance assessment	ANSYS Fluent CFX CHAM ALYA Custom Code

2.2.1. Simulation methods

A number of numerical studies concerning air-based PVT and BIPVT has been conducted the past decade, which are well documented and shall not be described in its entirety here. Yang and Athienitis [21] identified four main categories, which are displayed in Table 1.

MATLAB is in common use as well. A detailed numerical model was developed by Slimani et al. [37] in order to compare four PVT configurations. Models for the electrical and thermal behavior were derived from combining numerous energy balance equations and material properties. Low deviation rates were found for the predicted module temperature although electrical power prediction was not as precise. COMSOL can be added to the list above, since researchers have begun using it as well. Chialastri and Isaacson [38] built a 2D model in COMSOL to assess and optimize a naturally ventilated BIPVT system. The authors noted that the software used accepted only fully opaque or transparent to specific spectral bands materials, which limited the realistic validity of the results and primarily served as comparative analysis of prospective configurations. It was stated that the boundary conditions were based on real life measurements, yet these were static values of arbitrarily chosen date and time, which does not differ too much from selecting steady state boundary conditions based on typical meteorological data. A common practice among numerical studies detected was the use of steady state boundary conditions, which clearly does not reflect realistic PVT operation. To illustrate this effect on simulation models, Fan et al. [39] developed a model with dynamic boundary conditions, accompanied with experimental validation. The authors state that the model was more suitable for real time control of systems incorporating such collectors. Alternative assumptions could be explored as well. For modeling various configurations, with the intent of determining performance before construction and installation CFD models might be more appropriate.

The review of Lamnatou et al. [40] focused on the simulation and modelling of building integrated solar systems, which included air-based BIPVT configurations. The methods reviewed were categorized into energetic, thermal and combined energetic/thermal simulations, with utilized software listed. It was noted that there is significant difficulty transferring the results of detailed analysis like CFD into whole year system simulation environments. Debbarma et al. [41] also reviewed modelling approaches, listing software packages and mathematical formulation used.

CFD are being increasingly used in PVT related investigations. Software packages solve equations in order to analyze flow and heat characteristics of fluids. A short description of the governing equations is given below. Note that all equations apply for each finite volume element of the created mesh, signified by pointers i and j.

- Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \tag{1}$$

where ρ density and u velocity

- Momentum Conservation equation

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial [\rho u_i u_j]}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho f_i \tag{2}$$

where p pressure, f body forces (including gravity) and the stress tensor

$$\tau = \mu\left(\left(\frac{\partial (u_i)}{\partial x_j} + \frac{\partial (u_j)}{\partial x_i}\right) - \frac{2}{3}\frac{\partial (u_i)}{\partial x_i} I_{ij}\right) \tag{3}$$

where μ the dynamic viscosity and I the unit tensor.

- Energy Conservation Equation

$$\frac{\partial}{\partial t}\left(\rho e_0\right) + \frac{\partial}{\partial x_j}\left[\rho u_j e_0 + u_j p + q_j - u_i \tau_{ij}\right] = 0 \tag{4}$$

According to Fourrier's Law, the heat flux is:

$$q_j = -k\frac{\partial T}{\partial x_j} \equiv -C_p \frac{\mu}{Pr}\frac{\partial T}{\partial x_j} \tag{5}$$

where Pr is the dimensionless Prandtl number and e_0 the total energy defined as:

$$e_0 \equiv e + \frac{u_k u_k}{2} \tag{6}$$

where $e = C_v T$, with C_v the specific heat capacity under steady volume.

Boundary conditions typically include velocity variants like the no slip condition for fluids (velocity of finite volume equal to zero at wall) and thermal ones, like adiabatic condition for insulation or custom expressions from empirical studies. An example of the latter is convection from the cover surface to the ambient air. This is described by the following equations:

$$q = hA(T_{sur} - T_{amb}) \tag{7}$$

where A the surface area of the cover, T the temperatures of the surface and ambient while h the convection heat transfer coefficient which is calculated from the following empirical correlations:

- McAdams (1954) [42]

$$h = 5.7 + 3.8 \times u_{wind} \tag{8}$$

Table 2
Specifications of reviewed CFD studies.

Reference	Software	Model	Validation
Kim et al. 2023 [47]	Fluent	k-ϵ RNG 3D steady	Yes
Benzarti et al. 2022 [31]	Fluent	k-ϵ RNG 3D steady	Yes
Shrivastava 2022 [48]	Fluent	k-ϵ 3D transient	No
Perez 2021 [49]	Fluent	k-ϵ RNG EWT 3D steady	Yes
Kim et al. 2020 [46]	Fluent	k-ϵ 3D steady	Yes
Arifin 2020 [50]	Fluent	k-ϵ RNG 3D steady	No
Yu 2019 [44]	NX	k-ϵ 2D steady	No
Ömeroğlu 2018 [51]	Fluent	k-ϵ EWT 2D steady	Yes
Chialastri 2017 [38]	COMSOL	2D steady	Yes
Roeleveld 2015 [52]	COMSOL	k-ω 2D	Yes

- Watmuff (1977) [43]

$$h = 2.8 + 3 \times u_{wind} \tag{9}$$

To describe the convection between wind and collector

CFD studies range from component level to whole system configurations. Yu et al. [44] utilized the NX software package to analyze the flow within multiple collectors which would cover parts of the facade in a demonstration installation of BIPVT. Based on the results of the CFD analysis, the best performing case was chosen for application. The authors highlighted the importance of uniform flow and the connection topology of the BIPVT. The choice of the correct turbulence model in CFD calculations is critical for the correct numerical modeling of PVT devices. To investigate the heat transfer characteristics of Unglazed Transpired Solar Collectors (UTC), Li et al. [45] tested, validated and assessed the performance, of the following Reynolds-Averaged Navier-Stokes (RANS) models: Standard k-ϵ, Realizible k-ϵ, Renormalization Normal Group (RNG) k-ϵ, Shear Stress Transport k-ω and Reynolds Stress Model. It was concluded that the RNG k-ϵ delivered the highest accuracy and consistency, with low computational demand. The heat transfer topology and traits of UTCs are significantly similar to those of air based PVT and is therefore reasonable to extend this notion to the latter as well. A future study confirming this seems appropriate. One of the significantly few instances where validation occurs with data collected from standardized performance tests is encountered in the investigations of Kim et al. [46,47]. This is considered a scientifically sound approach and is further discussed in detail in the later section dedicated to the methodologies of PVT research. In Table 2, software packages and turbulence models utilized in recent studies along with some remarks regarding the implementation are presented.

2.2.2. Outdoors testing

Numerous experimental studies were performed outdoors, in different climatic conditions, testing air based PVT and BIPVT prototypes. Most outdoor testing was directed towards directly exploring the performance of new cooling concepts alongside a reference system, tested simultaneously at identical background conditions. As such, the general template followed by the investigations was to propose a new design, analyze the experimental method followed and provide the acquired performance enhancement, typically in percentage form. It remains a reliable way of illustrating enhanced operation of novel configurations, since they are internally and externally valid, yet such tests cannot provide global criteria or benchmarks that would enable direct assessment and comparison of technologies and designs from different research endeavors. In some cases, the data acquired was utilized to validate models as well.

Performing experiments in outdoor locations enables researchers to detect and quantify the effect of real phenomena in detail but without precise control over it. One such is the effect of wind, highlighted in a number of studies. Outdoor investigations mainly employ wind speed measurements through weather station data or cup anemometers. Few

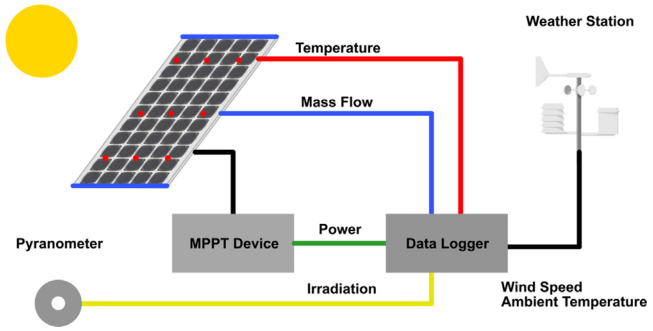


Fig. 6. Illustration of outdoor testing setup.

Table 3
PVT related parameters and recommendations.

Exp. Errors	Outcome
Omit Wind implication	Effect on Efficiency
Focus on Validation	Biased Results
Bad Calibration	Noisy Readings
Short term monitoring	Omit long term effects
Focus on one Season	Omit Seasonal Differences
No Uncertainty Analysis	Instrument Errors Unchecked

Table 4
Instrumentation of reviewed Experiments.

Measurement	Location	Instrument
Temperature	Ambient Inlet Flow Outlet Flow PV Module Air Channel	Thermocouples Infrared device
Mass flow	Inlet flow Outlet Flow Air Channel Wind	Hotwire Anemometers Cup Anemometers Mass Flow sensors
Irradiation	PV Surface	Pyranometer
PV Monitoring	PV Output	Voltmeter Ammeter Wattmeter MPPT Device

studies monitored the direction of the wind as well. Specifically Kaplani and Kaplanis [53] evaluated in detail through an experimental installation, the effect of wind velocity and direction on the heat convection of the PV modules. Findings showed that wind flow parallel to the PV surface leads to lower convection rates.

Assoa et al. [54] performed field tests for the validation of a thermal model that would predict the temperature profile of an air based PVT system. Array configurations with and without insulation were setup alongside a reference array. Flash tests were performed beforehand to verify the validity of the manufacturers data. Electrical monitoring took place both before and after the inverter connection, for DC and AC values. The differences between calculated and measured values was attributed to assumptions made in the model regarding the temperature of thermal nodes. Focus was given mostly to the validation of the model and there was no mention regarding the performance characteristics and enhancements of the insulated and non-insulated variants. An illustration of common setups is presented in Fig. 6.

It is important to calibrate and verify that testing equipment function properly. Zogou and Stapoutzis [55] experimentally tested outdoors and validated a model for a vertical BIPVT in three modes. It was highlighted that due to some malfunction in the maximum power point tracking routine, lower efficiencies were measured than what was calculated. Additionally, temperature readings with excessive noise were attributed to faulty thermocouple connections. Unlike the majority of studies, a more long term analysis was performed by Bot et al. [56], in which the temperature measurements of a BIPV facade and its naturally ventilated air cavity spanned over a period of one year and three months. This extended monitoring period can be applicable for examining energy behavior patterns not detectable in short span investigations, particularly long term thermal interaction with the building. Common experimental errors and their outcomes are shown in Table 3.

Certain studies did follow standard experimental procedures. Kim et al. [57] tested a PVT prototype with 2 axis tracker in accordance to the ISO 9806:2017 standard, noting that the measurement deviation values were acceptable. As a rule, detailed lists with the instruments used in experimental investigations are typically provided along with error ranges yet few are the studies that do perform an uncertainty analysis, in order to confirm the credibility of the results. Agathokleous and Kalogirou [58] used the standard error formula in their figures to illustrate measurement ranges with high uncertainty in a clear way. In a study exploring the performance of a combined air and PCM cooling configuration by Choubineh et al. [59] the relative uncertainty of the electrical efficiency and power were calculated using the law of uncertainty propagation:

$$u_c = \sqrt{\sum (c_i u_{Xi})^2} \tag{10}$$

where u_c is named the combined uncertainty, c_i is the sensitivity coefficient and u_{Xi} the uncertainty of each measured variable X_i. A more general form, addressed to experimental measurements in particular, can be found in the guidelines that ASHRAE has published for calculating uncertainty in energy measurements [60]:

$$RE_c = \frac{\sqrt{\sum (RE_{instrument} \times r_{rating})^2}}{\sum \bar{r}_i} \tag{11}$$

where RE_c is the combined relative error, $RE_{instrument}$ the relative error of each instrument at some rating point r_{rating} and $\bar{r}_i$ the mean reading of any instrument.

The basic measurements most researchers seem to carry out and the corresponding equipment used in the experimental process are as presented in Table 4.

2.2.3. Indoors testing

Concerning testing performed in a controlled environment, like a laboratory, the largest part was dedicated for the validation of analytical or numerical models. Thus, constructing a model and then validating it in a laboratory test provides flexibility in early stage sizing, parameter analysis, economic assessments, prospective application scenarios etc.

Agrawal and Tiwari [61] evaluated the performance of a PVT cell air cooled with microchannels using a setup comprised of 28 tungsten halogen lamps. The irradiance intensity was regulated by adjusting the height between cell and lamps through a manual mechanism, which arguably is difficult to control systematically.

The main issue with this approach is to be able to directly compare the performance of different prototypes under the same conditions. The results do reflect reality but then measurements under different operational circumstances are taken into account. It is clear that a testing benchmark needs to be established.

Solanki et al. [62] constructed a testing setup suitable for air cooled PVT measurement, aimed at researchers and manufacturers. The solar simulator consisted of tungsten halogen lamps, arranged for uniform irradiation output, according to the authors. It was noted that this method of testing was more economical in comparison to current approaches. No information was provided regarding the process followed to achieve this. Similarly, there was no description of how the heating effect from the infrared spectrum of the lamps was allegedly negated by the use of an exhaust fan. Studies with indoor testing mostly follow configurations like this. The gaps in these testing approaches are evident, illustrating the need for more reliable testing and measurements.

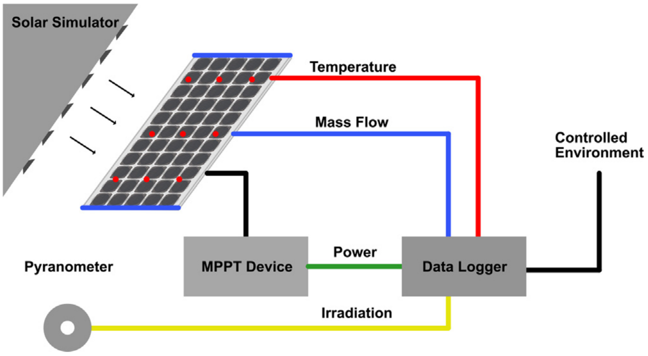


Fig. 7. Illustration of outdoor testing setup.

To investigate the synergy of corona wind and air based cooling in PVT applications, Golzari et al. [63] constructed two setups, one in the laboratory and one in the field, for testing the proposed PVT system. Corona wind was found to positively affect the efficiency of the PVT system. The experiment involved the use of four 1000 W tungsten halogen lamps, with the distance between lamps and absorber regulating the irradiance intensity. As is typically the case, a detailed listing of the instrumentation is provided, yet a comprehensive description of the experimental process is missing. Furthermore, rather high values of uncertainty are reported for the equipment. For such circumstances, a section with uncertainty analysis would be highly motivated yet the vast majority of studies tend to omit this.

Fudholi et al. [64] experimentally examined the exergy and sustainability of a PVT collector with delta shaped corrugated absorber attached to it. The solar simulator used was composed of 45 x 500 W lamps, in order to test two different radiation levels. No information was provided about the kind of lamps or how closely they emulated the real solar wavelengths. The study used a higher number of lamps than average, resulting in greater electrical consumption.

A typical indoors configuration is shown in Fig. 7.

Mojumder et al. [30] designed and tested a PVT prototype with fins for cooling, which enhanced the thermal efficiency by up to 56%. The experimental configuration included a solar simulator comprised of 2 x 1000 W and 3 x 500 W halogen bulb lamps. In order to ensure accurate radiation values, three runs of measurements at nine points on the module were completed, thus achieving a module total average very close to the target solar radiation of 700 W/m^2. This procedure is documented in ISO 9806:2017 [65] and is followed by the researchers in detail. Other measurement parameters defined by the certification standard include the positioning of the airflow temperature sensor, the placement of insulation, a steady state monitoring with emphasis on ambient temperature and the accuracy of the velocity measurements.

Ooshaksaraei et al. [66] constructed four air based PVT prototypes with bifacial solar cells and tested them in controlled conditions. A solar simulator was utilized, with 45 x 500 W tungsten halogen lamps each with its own dimmer in order to minimize the irradiance non-uniformity. This configuration can be cumbersome to calibrate and in the end not not realistic enough, since the non-uniformity was found in the 6–8% range, resulting in a class C solar simulator. The testing procedure was well documented though and researchers are prompted to follow a similar structure when explaining their own.

The experimental process followed is as important for the validity of the results. Bigaila et al. [67] shared a more detailed account of the procedure they followed to assess the operation of an open loop PVT collector prototype. Specifically, a mass flow range from 25 to 400 kg/h at three different wind conditions and varying irradiation levels was tested alongside temperature measurements of the back PV surface every 5 seconds. The module was connected to an electronic load to ensure operation at optimal power point. Table 5 lists indoor tests and their limitations.

Table 5
List of Indoor studies.

Reference	Limitation
Fudholi et al. 2019 [64]	No info about testing rig
Golzari et al. 2018 [63]	Exp. process description missing
Ooshaksaraei et al. 2017 [66]	High non-uniformity
Bigaila et al. 2015 [67]	No info about load
Agrawal and Tiwari 2011 [61]	Manual mechanism for irradiance
Solanki et al. 2009 [62]	No info about IR heating

A methodology suitable for the direct comparison of the thermal performance in PVT and BIPVT systems was developed by Rounis et al. [68]. Emphasis was given to its dimensionless character and a more direct fashion concerning. In particular, the experimental procedure involved the following parts. A solar simulator comprised of 8 metal halide lamps, meeting ISO 9806 and EN 12,975 specifications. Artificial sky, ventilated by air, intended to minimize the effect of infra-red wavelengths generated by the lamps. A linear fan emulates wind effects. Parameters such as mass flow rate, PV transparency and air duct aspect ratio were also an important part of the process. Utilizing this methodology, satisfactory agreement between experimental findings and the predictions was observed, additionally noting that it can be tailored to individual systems. The investigation required the use of high-end equipment, uneconomic and complex to operate which is at odds with the authors' aim of developing a universal testing approach. Solar simulator setups are generally significantly expensive, thus hindering the wide-scale investigation of PVT systems. In this sense, focus should also be given to creating accessible experimental procedures, mainly through simplified yet reliable testing rigs and procedures.

Alternative approaches, in terms of experimental setup, have been attempted as well. Lin et al. [69] studied in particular optimal strategies for the use of Phase Change Materials as thermal storage in air based PVT. In this experimental setup, the researchers did not employ an actual PVT device but rather emulated it, with a combination of an electric heater and a variable speed fan. Thus, through the use of a Proportional-Integral (PI) controller, mass flow and temperature levels of the airflow could be regulated. Rather simple yet robust, such a test is not enough to capture important aspects of heat transfer in PVTs, like complex thermal interaction between multiple layers made of different materials, air leakage, ambient climate conditions etc. As such, this approach can deliver results quickly with minimal setups, yet cannot provide in depth, externally valid examination.

In brief, the methodology of PVT investigations was scrutinized. Starting with simulation methods, techniques and packages were listed, with CFD applications being the most common. Concerning the latter, the governing equations, validation and turbulence models were discussed, of which the k-epsilon had widespread use. In the outdoor experiment subsection, factors that affect investigations were mentioned, for example wind effects, while attention was also given to possible errors that might arise during the experimentation process. Additionally, it was deemed that uncertainty analysis plays an important role as well. For indoor studies, the equipment and instrumentation were critically assessed, mainly questioning whether the controlled environment can successfully emulate real conditions.

2.3. Integration

While the focus of PVT research has primarily been on understanding and improving heat transfer, a lack of investigations into its application and system-wide solutions in buildings has been identified. This can either be facilitated by connection to the buildings' energy systems and/or the direct integration into the building envelope. Chen et al. [70] tested the interaction of a BIPVT system with a nearly Zero Energy

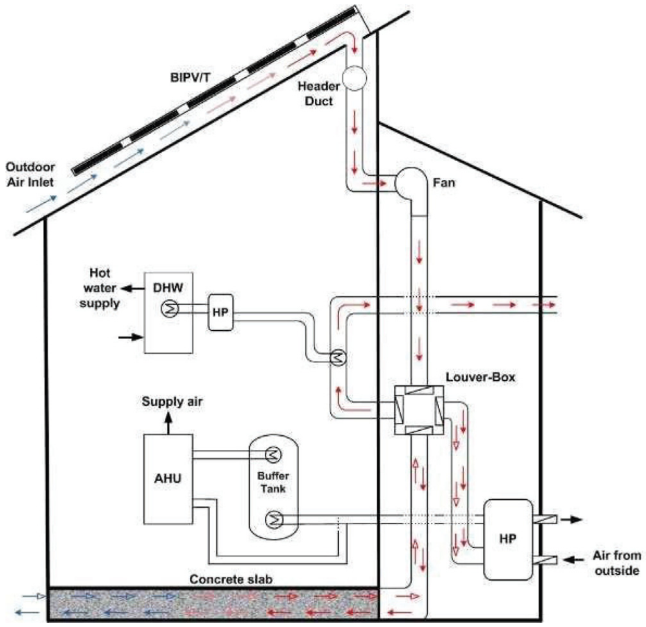


Fig. 8. System analyzed by Kamel et al. [71], including ventilated concrete slab. Under CC BY-NC-ND 4.0 license.

Building (nZEB) situated in cold climatic conditions. It was highlighted that instead of assembling on-site, prefabricating the systems provided benefits like leakage free and thermally insulated flow. The installation could also take place in winter, which would not be possible otherwise requiring on site work.

The combination of Air-Source HP and BIPVT for heating in winter was setup by Kamel et al. [71]. The system incorporated thermal energy storage, specifically a ventilated concrete slab, shown in Fig. 8. Controlling the combined operation of the heat pump and thermal storage in different weather conditions was a difficult task. Additionally the connecting ducts from the BIPVT to the HP required significant engineering. To address this, a louver box with dampers was proposed, allowing the directed airflow to different applications based on the implemented control strategy. However, the highly custom design limited the scope of the study.

Bambara [72] monitored the operation of an Unglazed Transpired BIPVT configuration, in real working conditions. Minimal distance to the mechanical room and orientation were deemed crucial for the operation. 33% of the ventilation heat demand was covered by preheating the fresh air supply.

Three BIPVT integration schemes were explored numerically by Ma et al. [73]. The output could either be connected to a HP, used to preheat air for the heat recovery ventilator (HRV) or even directly used for space heating. The last configuration could in the end not satisfy the comfort requirements and was therefore rejected. For the rest, defrosting was a severe limitation to the operation, offsetting energy savings achieved. Bigaila and Athienitis [74] opted to decentralize the generation and storage of thermal energy, by designing BIPVT façade panel encapsulates with integrated micro-HP and short duration PCM storage. The system along with the prefabrication strategy utilized, contributed to reduced installation time and complexity, are particularly beneficial for retrofit projects. Significant planning is required although. On larger scale analysis, Hassan et al. [75] studied the combined operation of ASHPs with BIPVT for five different locations. Among the parameters that had significant impact on the operation were the local geography, local climatic conditions, energy mix of the district, building regulations, function and morphology of the site.

Yu et al. [44] investigated BIPVT prototypes mounted on a southern facing facade, which supplied preheated air to an air handling unit (AHU) as well as electricity to a building of a school. The internal path of the air flow and the connection between panels were highlighted as important for efficient operation.

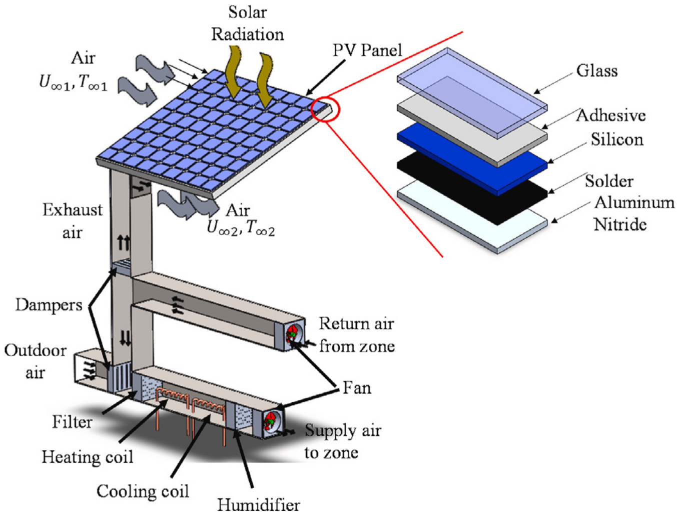


Fig. 9. Inverse system by Salameh et al. [80]. Under CC BY 4.0 license.

Solar energy displays a stochastic profile and requires therefore some form of storage to cover loads during the whole duration of the day. Lamnatou et al. [76] reviewed storage systems compatible with BIPV and BIPVT. The review noted that batteries have become widely used for electrical energy storage in residential applications and analysed environmental and economic parameters including capacity, lifecycle, degradation, safety risks, recycling, toxicity. Meanwhile, the utilization of PCM for thermal storage is gradually gaining momentum. Higher cost and challenging disposal were among the issues identified. In contrast, the simpler option of water storage tanks was examined from technical, socioeconomic, and safety perspectives, as well as the environmental impact of their constituent materials. The analysis indicated that water storage displays smaller environmental footprint, extended integration capabilities and longer lifespans, of up to 30 years.

The lack of data sources regarding the operation on the system level was criticized by Brahim and Jemni [77]. To promote the implementation of standardized solutions and disseminate the technology, they advised increased deployments and demo sites with long-term monitoring. Al-Waeli et al. [78] claim commercial development of PVT technology depends on the creation of reliable standards. The aesthetic integration plays a role as well. The decision to either camouflage or showcase building integrated designs was discussed by Kuhn et al. [79] particularly by adding varied color schemes and patterns. Additionally, a market analysis was performed. It was concluded that new demonstration installations can elevate awareness around the technology and contribute to installation know-how.

The common practice of PVT technology is to use the heated air to provide energy to building systems. Salameh et al. [80] inverted this procedure by utilizing wasted cooling from building energy system to reduce BIPV surface temperatures. Exhaust air from the HVAC system was connected to BIPV panels instead. This led to elevated production of electricity. Findings favored minimal air duct height. An interesting proposition was to add an auxiliary channel for preventing accumulation of particulate matter on the PV surfaces. The system is shown in Fig. 9.

The mode of operation was studied by Ahmed-Dahmane et al. [81] who distinguished operation for winter and summer weather conditions. In the former air warmed by the panels was supplied to the AHU, resulting energy savings. For the latter, air from conditioned interior spaces cooled overheated PV surfaces. A single flow rate was tested. The testing of multiple flowrates were recommended in order to evaluate the system level operation.

From the control aspect, limited research is found. Sigounis et al. [82] developed a MPC controller for higher energy efficiency, mainly by supplying multiple thermal applications instead of only singular ones. Heated air could be supplied to either of HRV, HP or AHU, in different quantities. The authors highlighted that the model was too reliant on correct weather predictions, therefore introducing uncertainty. Additionally control should be implemented on full building level, ideally with real time interaction.

In essence, various configurations for the utilization of the generated thermal energy in buildings have been proposed and tested, with many setups employing HPs or AHUs, facing difficulties mostly from a technical aspect. Direct use and storage has been somewhat avoided, although the latter seems to have potential.

3. Proposed solutions

In this section general directions based on the previously examined roadblocks are given.

3.1. Performance enhancement

In Solar Air Heater (SAH) research, the enhancement of heat transfer through inserts has been investigated extensively. The heat transfer taking place in air based PVTs is significantly analogous to that of SAH, mainly due to highly similar heat transfer phenomena and boundary conditions. With this in mind, in the following section SAH inserts with validated performance and their appropriateness with PVT technology are analyzed. Proposals for additional enhancement are brought forth.

Air has a lower thermal capacity than water yet for certain thermal applications it beneficial to use the former as a heat transfer medium. SAHs have a proven track record in drying applications or contexts where lower temperature rise is required. In recent literature, two of the main methods of improving the transfer of thermal energy are to disrupt the local thermal boundary layer or increase the turbulence of the flow [83]. Heat convection rate is elevated in turbulent flows due to its tumultuous movement. In forced convection applications, flow particles that are adjacent to solid surfaces are slowed down due to friction which leads to reduced heat transmission. The section of the flow displaying this damped down transfer is called the thermal boundary layer. To reestablish thermal attributes found in the free flow, this layer can be disturbed by artificial means. A wide range of surface modifications or additions can have this effect, as Rashidi et al. [84] pinpointed in their review, which covered vortex generators, twisted tapes, baffles and wired coils. Each of the techniques was analyzed according to their performance and their possible applications. It was stated though that there were limited economic investigations to be found, which would illustrate the viability of these additions.

Promvonge and Skullong [85] defined baffles and winglets as extremely thin ribs. The distinction between the two is made, when their height covers 25% or more of the channel and the attack angle is 30° or more.

To evaluate the elevated heat transfer of new designs, but also taking into account the inevitable rise in friction, the Thermal Enhancement Factor (TEF) was introduced. It is defined as:

$$TEF = \frac{\frac{Nu}{Nu_0}}{(\frac{f}{f_0})^{0.33}} \tag{12}$$

where Nu the Nusselt number and f the friction factor of the new design. The subscript 0 denotes the initial, unmodified channel. It essentially quantifies how well convection heat transfer is enhanced while maintaining pressure drop.

A few enhancement methods are described below, which seem promising for PVT applications.

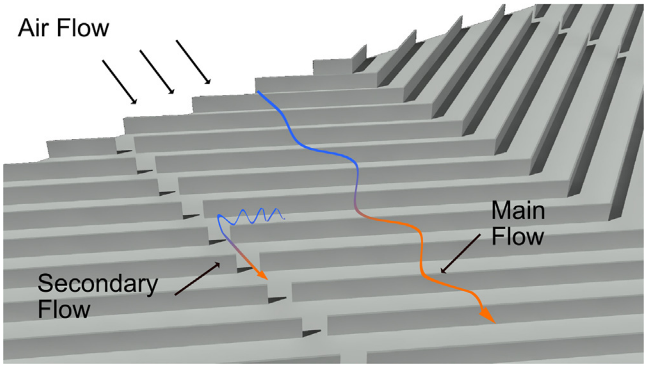


Fig. 10. Illustration of V-baffle and flow characteristics.

3.1.1. Baffles

Baffles are surfaces that divert airflow in a specific manner in order to disrupt the thermal and laminar boundary layer. The profiles can be of various geometrical shapes. When the fluid hits the baffle edge, flow separation occurs, causing the flow to recirculate and impinge back to the surface. Additionally, secondary flows form, further improving mixing and heat transfer albeit with higher friction. Combinations of parameters determine optimum thermohydraulic performance. The key ones have been designated as the ratio of pitch and of the blocked channel area as well as the relative attack angle of the flow. Various morphologies have been investigated, evaluating shapes like U [86], Z [87] and cubes [88]. V-shaped baffles have displayed promising performance enhancement with consistently high TEF designs. V-shape baffles disrupt the main flow at regular intervals, creating secondary flow jets, which progress along the length of the baffle.

Tamna et al. [89] investigated the addition of baffles to one or both sides air channels. The single arrangement exhibited higher TEF rates than the double counterpart, due to the lower blockage ratio. Concerning double arrangements, the in-line type attained marginally better results. Fawaz et al. [90] came to the same conclusion regarding the reduced blockage, by numerically testing different in-line configurations and their periodic flow behaviour.

Discretized broken V-shape baffles is design variation in which secondary flows are directed through gaps along the baffle leading to the acceleration of the main flow Kumar et al. [91] studied this configuration and confirmed that the decelerated boundary layer is energized anew. Optimal performance was dependent on characteristics like the size and position of the gaps.

To reduce the friction caused by baffles and create additional secondary flows, Promvonge and Skullong [85], combined perforated designs with flaps from square shaped cuts on the baffles. This allows the flow to pass through the cavities and be directed towards the absorber surface, creating thus impingement jets. These modifications accounted for reduced pressure drops and additional cooling. Optimal ratios for pitch and flap angles were determined.

An illustration of the V-baffle is given in Fig. 10.

Eiamsa-ard et al. [92] utilized semi-circular flaps instead, in order to restrict dead zones downstream of the baffle. Greater overall performance was observed.

3.1.2. Vortex generators

Vortex generators (VGs) increase heat transfer in fluid flows by creating vortices. A vortex refers to the swirling motion of a fluid, in which the fluid either revolves around a central axis or exhibits confined rotational movement. VGs are typically use on aircrafts in order to delay the separation of flow over the wing. This interaction can be beneficial for heat transfer applications as well since The unseparated flow prevents the formation of thermal boundary layer downstream. VGs of different profiles have been studied in SAH research, such as rectangular-shaped

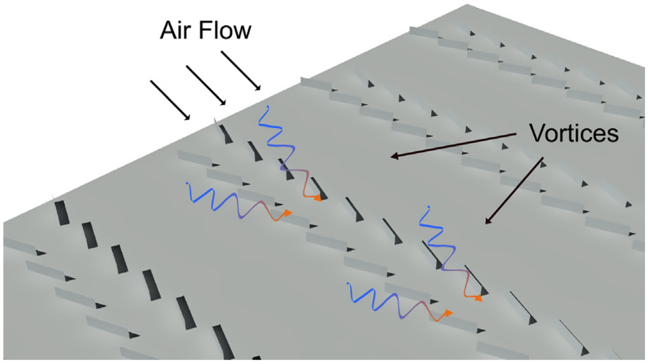


Fig. 11. Illustration of VGs and flow characteristics.

[93], trapezoid-shaped [94], delta-shaped, curved [95] and truncated half conical [96]. Friction increase caused by blockage of the flow is to be expected. A VG configuration is shown in Fig. 11.

Delta-shaped winglets with wavy features were investigated by Sawhney et al. [97]. The goal is to create sets of vortices, which interact, superimposing their secondary flows into one direction for greater effect. These break down after some distance, leading researchers to investigate pitch ratios that reinforce the vortices at regular intervals.

Perforated designs were studied as well. Smaller blockage leads to reduced friction. The Friction and thermal characteristics of perforated and non-perforated curved delta-shaped VGs were studied by Baissi et al. [98]. In every perforated case reduced friction and improved TEF were detected.

Hole diameters of perforated VG designs were evaluated by Skullong et al. [99]. Highest TEF was encountered with a hole diameter of 5 mm. The positive effect of combining VGs with other methods such as grooves [100] or ribs [101] has been documented as well.

Dezan et al. [102] wanted to optimize a set of nine VG parameters. First row angle and chord had the most impact. High performing configurations displayed a tendency of creating longitudinal vortices along the main flow direction and close to the heat transfer surface.

3.1.3. Impingement jets and ribs

Adding inserts in SAH increases friction and to limit this effect researchers found that reduced size might be a solution. A method is to disrupt the thermal boundary layer by creating artificial roughness on the heated surface through extrusions, called also ribs. The result is separation and reattachment of the flow at intervals. Impingement jets is the method of striking a surface with a jet, in order to augment convection and minimize the thermal boundary layer. The synergy of the two techniques can enhance performance even further. A selection of rib profiles were analyzed numerically by Ngo and Phu [103] evaluated different rib shapes and determined that hyperbolic ribs were most suitable. Hyperbolic ribs have a smooth profile which led to minimized areas of reduced convection, upstream of the rib. The broken V-shape but this time with ribs, was investigated by Deo et al. [104]. Increase in TEF was achieved by optimizing the rib geometry. The rib arc shape with broken, staggered and combined configurations is also used [105–107]. A SAH equipped with a cross-flow jet plate was investigated by Nayak and Singh [108]. Longer spacing between jets and higher flowrates were preferred. Heat transfer was improved while pressure drop remain somewhat stable and was thus considered beneficial for SAH operation. N. Kumar et al. [109] examined conical ring obstacles for use with impingement jets. The rings did enhance heat transfer because they introduced lengthier swirl paths.

3.1.4. PVT And SAH parallel

The hypothesized combination of PVT with thermal inserts developed for Solar Air Heater is illustrated in Figs. 12 and 13.

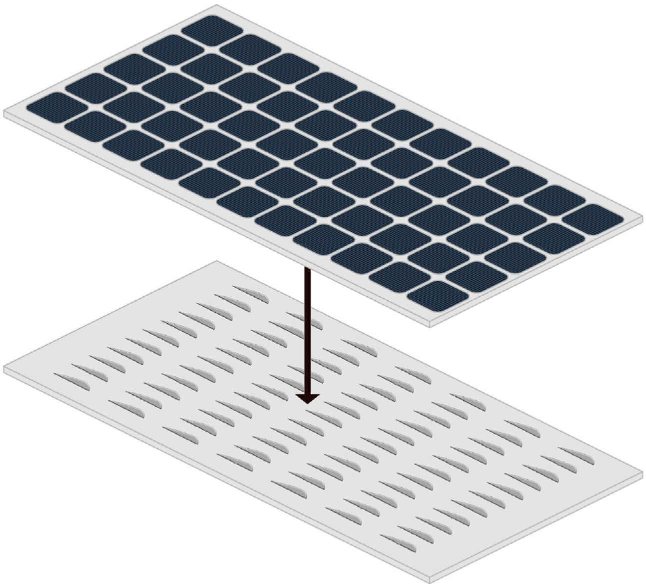


Fig. 12. Illustration of the layout of PVT with inserts.

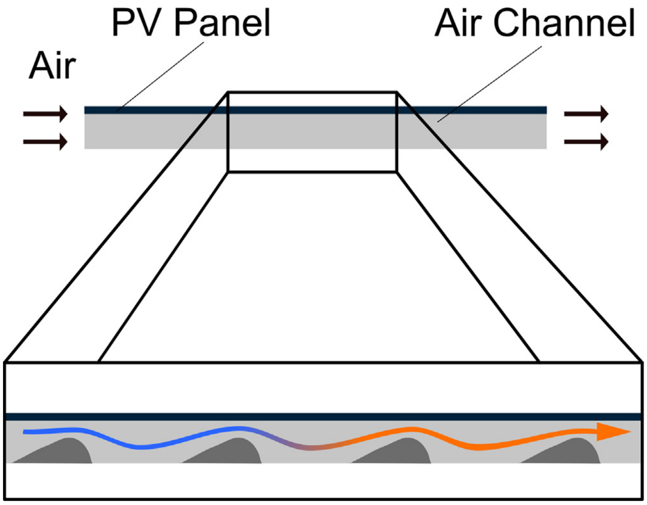


Fig. 13. Illustration of the operation of PVT with inserts installed in the air channel.

Studies investigating air-based PVT systems were restricted to regular air channels and the addition of fins. Drawing insights from SAH research, the proven impact of inserts could be beneficial for enhancing the performance of PVT systems and should be further explored in PVT and BIPVT investigations. Given the technical similarities, it is reasonable to draw a parallel between SAH and PVT collectors. The prospect of enhancing heat removal is significant, with the goal of cooling PV surfaces and generating low grade thermal energy. However, it is essential to consider operational and design differences to identify the most suitable methods for PVT applications. Considering modules, maintaining uniform temperature is critical. Otherwise significant temperature gradients are created along the PV surface. Such gradients cause different cells to generate at different maximum power points, minimizing durability and electrical efficiency. To prevent the formation of hot and cold areas, uniform cooling is needed. Flapped or perforated baffles fit this description, by limiting the reduced heat transfer zones. Combining vortex creation and impingement jets, can further enhance spatially even heat removal. Modifying the SAH absorber surface through various manufacturing processes can achieve the desired morphology to enhance heat transfer, including adding ribs or protrusions. However,

Table 6
PVT related parameters and recommendations.

Parameter	Recommended Approach
Uniform Cooling	Perforated Baffles
Low Weight	Vortex Generators
Backplate Manufacturing	3D Printing
High TEF, low ΔP	Optimal Inserts

in the case of PVT, it is the PV surface area that is heated, and the backsheet material, usually made of tedlar, presents challenges in processing. Future designs should consider this material difference.

BIPVTs have additional specifics to be addressed, in particular regarding the system weight. Low weight solutions need to be developed to prevent damage of building envelopes. Materials with significant weight, such as specific metals, are limited in that scope. Polymers, do not suffer from this yet have low thermal conductivity. This is changing though with high conductivity polymers being developed as of recent. To create intricate baffle geometries, 3D additive manufacturing can be utilized, which has progressed significantly as of late. Currently polymers, composites and metals can be used. Ribs and VGs are possibly appropriate for this end due to the reduced material needed. Ultimately, the designs need to limit the pressure drop in order to minimize pumping power. Low friction configurations with high TEF values should be preferred.

In short, thermal augmentation solutions that have been developed for SAH applications are fit for implementation in PVT as well. The high potential of Baffles, Vortex Generators and Impingement jets methods has been identified and analyzed. Table 6 summarizes recommended approaches for different parameters.

3.2. Guidelines for experiments

Guidelines for methodology in future research is compiled in this section.

The most common simulation practices were presented in the respective subsection. It is vital to validate any analytical, numerical or CFD models, in order to ensure the validity of results. Thus, it is advised to include a validation process early in the planning phase of simulation investigations. Regarding turbulence models, the use of the $k-\epsilon$ RNG model is advocated, due to its reliability, low computational demand and suitability for subsonic turbulent internal flows. So far, boundary conditions are based on steady flows. For more realistic insights, it is advised to explore dynamic boundary conditions.

In general, a reliable standard for testing indoors and outdoors methods is described by ISO 9806 [65]. Specifically it outlines standardised methods for testing the thermal performance, but not the electrical, alongside safety, durability and reliability testing. It is applicable to hybrid solar collectors, in this case air cooled PVT. For all thermal measurements the collector needs to be connected to a load at maximum power point. Some tested features include air leakage tests, stagnation temperatures, exposure tests, impact resistance etc. However in this context of comparative performance analysis of novel designs, the applicable parts are that of thermal performance testing procedure, instrumentation, test installation, collector mounting and location as well as the determination of the pressure drop. The importance of the latter needs to be emphasized, since substantially few studies reported pressure drop of their designs, even if it comprises a critical criterion for determining their cost-effectiveness. A section dedicated to the assessment of uncertainty is also included. The current version was published in 2017, with the next revision planned for 2022–2023. Indoors and outdoor rigs are typically the same and distinguished into 2 methods, the closed-loop testing and the open-to-ambient. The operational difference of those configurations is the ability to control the inlet temperature by means of an electric heater in the closed loop while only ambient temperature is available for the open loop. The difference of indoor and outdoor cases the collector and solar simulator are situated in a way to achieve normal irradiation whereas in outdoor cases either a tracker can be utilized or a stationary rack, the latter limiting the total hours of normal irradiance. Schematics visualizing the configurations of a ISO 9806:2017 performance test are found in Figs. 14 and 15. The EN12975 standard [110] is directed towards all types of fluid heating solar collectors, including air-based PVT. In general almost all information regarding testing is redirected to the ISO 9806, some new performance rating parameters are introduced, needed for subsidy schemes and for other purposes of public interest. Researchers are encouraged to follow these procedures, in order to obtain an standardized evaluation of the thermal performance for PVT systems.

As for the electrical side, since the vast majority of studies do not and probably will not construct PV cells from scratch, electrical related PV properties are provided by the manufacturer. In principle, the process for measurements is straightforward, where the output power is measured at maximum power point and the electrical efficiency is calculated. Fan consumption should also be monitored, for examining energy balance and economic viability. A short section is dedicated to the

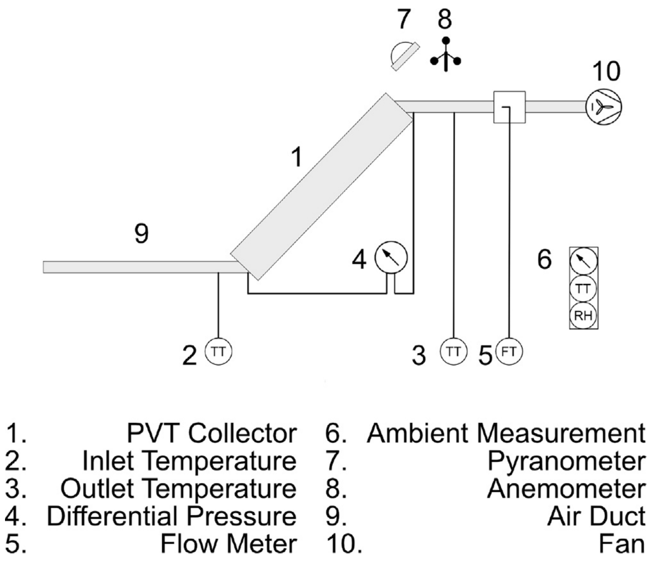


Fig. 14. Schematic of open-to-ambient ISO 9806:2017 performance test.

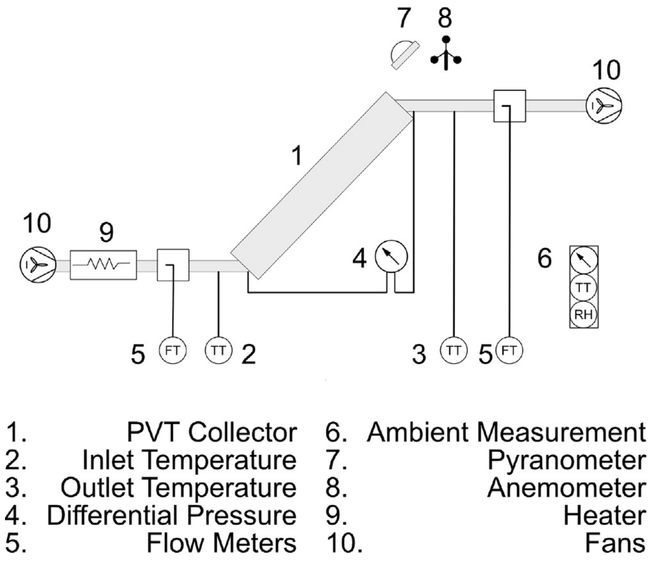


Fig. 15. Schematic of closed-loop ISO 9806:2017 performance test.

Table 7
Experimental Procedure and related remarks.

Process	Remarks
Calibration	All Instruments
Flow Measurements	Inlet flow
	Outlet Flow
	Air Channel
	Wind
Irradiance Measurements	Avoid Shading
	Calibrate Solar Simulator if needed
Electrical Measurements	$V_{\max}$ and V_{oc}
	$I_{\max}$ and I_{sc}
	Maximum Power Point Tracking
Temperature Measurements	PV cells, shielded from light source
	Inlet, Outlet, Intermediate space
	Walls
	Ambient
	Preferably multiple points
Calculations	Electrical Power P
	Electrical efficiency $\eta_e = \frac{P}{GA}$
	Thermal efficiency $\eta_{th} = \frac{\dot{m}c_p\Delta T}{GA}$
Uncertainty Analysis	Error of instruments or models
Validation	If simulation was performed

electrical yield of hybrid collectors (named co-generating in the report) in EN12975.

Performing the above measurements shall in turn provide researchers with temperature, mass flow, irradiance, power readings with which electrical and thermal efficiencies can be calculated. For the direct comparison and characterisation of PVT systems, Rounis et al. [25] listed different different key performance indicators (KPIs) proposed from other investigations. These included combined efficiencies, primary energy savings and an exergy method. To calculate those, all previously calculated and measured data can be utilized. Reliable KPIs should be adopted by future experimental explorations, given their utility in illustrating critical information in a clear and accessible manner.

Studies with deficient setups and solar simulators or cases which lacked information to that regard were reported as well. Researchers investigating PVT systems in the lab ought to utilize solar simulators that closely match the wavelength spectra of the sun. Certain technologies are proved to be reliable, yet can be rather expensive or complex to operate. Tawfik et al. [111] examined the four main types of light sources utilized in solar simulators, namely argon arc, xenon arc, tungsten halogen and metal halide lamps, describing their attributes and compiling guidelines based on the requirements of the selected application. It was concluded that xenon arc and metal halide lamps were the primary types used by researchers, due to their close spectral match to real sunlight. However, xenon lamps do require complex supporting equipment, rendering them more costly. Metal halide lamps have been therefore preferred recently. LEDs have been gaining traction lately due to their low capital and operational cost [112]. Leary et al. [113] directly compared a xenon lamp based simulator with a LED one and concluded that the latter was superior, even though there was spectral mismatch after 1100 nm. It is therefore recommended to consider these light sources when selecting or constructing a solar simulator, with LEDs being in general more affordable than the rest, given the recent advancements in the field. Certification and classification of solar simulators according to various attributes is described in the IEC 60904-9 standard [114]. The solar simulator used should be compliant to this standard.

All in all, it is suggested to test in standardized manner, for the sake of obtaining comparable results and determining suitable KPIs. Current literature has mostly based its investigations on ISO 9806, EN 12975 and ASHRAE 14 documentation. Furthermore, the testing process should resemble the basic structure described in Table 7.

3.3. Integration concepts

Studies exploring applied aspect of installations are limited. Concepts for encouraging more diverse and multi-functional integration are discussed below.

3.3.1. Low temperature heating

Waste heat from PVT cooling has low exergy [64]. It is therefore sensible to utilize this kind of heat source for applications with low exergy requirements, like space heating. Emphasis must be given in particular to Low Temperature Heating (LTH), due to the relatively lower temperature increase needed, leading to reduced exergy destruction. Sources with higher exergy, like electricity, can be utilized in applications not related to heating. It has been showcased that RES are highly suitable for LTH implementations, like geothermal [115]. In typical heating systems, ventilation radiators draw cold fresh air from the ambient environment and heat it by forced convection over radiators. An air-based PVT can potentially supply the ventilation intake, already preheated, therefore reducing consumption.

3.3.2. Ventilation heat recovery

Heat recovery ventilation systems aim to reduce heat losses inherent in ventilation systems by warming the supply air from the exhaust air outlet, which has been heated by the indoors heating system. This intake can be replaced by PVT air output, which essentially preheats the necessary ventilation supply. In an experimental investigation, Ahn et al. [116] presented the layout of such a coupled system. Only the addition of connecting duct and dampers were needed. Higher heat transfer efficiency in the HRV was reported. In this manner, configurations that facilitate the synergy of BIPVT and ventilation systems without requiring complex topologies or drastic overhauls are recommended.

The combination of heat recovery ventilation and LTH can provide significant savings in primary energy and increase of COP values of heat pumps, as demonstrated by Wang et al. [117]. The authors highlighted the selection of a more effective, preheated supply for LTH. PVT preheated airflow can potentially fill this operational gap adequately.

3.3.3. Energy storage

Energy storage is critical for the operational flexibility of residential energy systems which in turn is instrumental for the transition to carbon neutral buildings. Hot water storage tanks, a mature technology, are well established and part of a considerable portion of existing heating and DHW systems. Air-to-water heat exchangers offer reliable means for the synergy of BIPVT and hot water storage tanks. Efficiency of water-to-water heat exchanger is greater than that of air-to-water, yet the latter is possibly capable of offsetting the difference due to the easier implementation and subsequently larger area coverage. Integration wise, this method would require the least amount of interference, involving only the installation of the heat exchanger and the ductwork up to that point. In an initial phase, the heat generated could prospectively supplement some already installed heating source. However, attention should be given to the smart control of the combined systems. Advancements in the modelling of thermal storage should result in realistic complete system simulations, thereby assisting researchers developing optimal operation strategies, based on selected criteria. As noted previously, not only do different geographic locations have different operational and climatic conditions, a system might function in an alternate manner depending on the time of the year. Thus, it is advisable to develop multiple operation modes or strategies for several seasons and climatic zones. Storage should not be constrained to water tanks only however. PCM and sorption storage are gaining traction recently, offering diverse operational modes. Combined systems, like PCM tablets in water storage tanks, can be the stepping stone for enabling new storage techniques in residential applications. The passive charging of building elements, like concrete slabs is a promising alternative as well, as illustrated by Chen et al. [70].

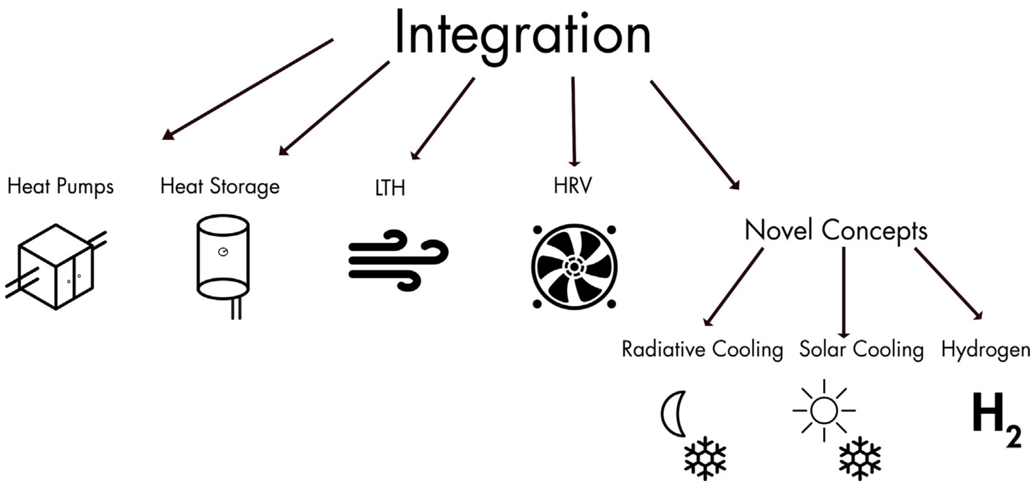


Fig. 16. Integration Concepts.

3.3.4. Heat pumps

Most PVT and BIPVT application investigations included some form of combination of energy storage and heat pumps. Experimental studies detailing the direct coupling of PVT with Heat Pumps were limited to only water or refrigerant based PVT systems. A detailed description of such systems can be found in the review of Miglioli et al. [118]. Concepts intended for air cooled BIPVT have been proposed and numerically modelled, yet applied configurations are lacking, leading therefore to gaps regarding their application. Future research should examine such concepts, on site.

3.3.5. Retrofitting and renovation

The focus on newly built structures limits the application range for BIPVT technology. Renovation and retrofitting potential is often overlooked in studies, despite the great part of the existing building stock is old and in need of energy system upgrade. This is outlined in a study by Saretta et al. [119] that reviewed tools and methods for BIPV potential evaluation and their dissemination in general. An analogous approach should be implemented for BIPVT, especially given the enhanced capabilities in regards to heating. Thus, researchers are urged to explore designs related to retrofitting installations of energy systems.

3.3.6. Novel integration concepts

New application concepts that enhance the multi-functionality might be the catalyst for a more widespread dissemination of PVT technology. One key issue with solar thermal energy is the mismatch of availability and demand. particularly in terms of seasons. Hence, in summer, with peak thermal generation, the demand for heat is low but instead a great amount of cooling is required. Solar cooling might be able to bridge that gap and in the case of air based PVT, desiccant cooling seems promising. The compatibility of air based PVT as low temperature sources with desiccant cooling and dehumidification is discussed in a review by Guo et al. [120], illustrating their potential. Thus, their effective utilization is extended to the warmest period of the year as well.

In similar fashion, night radiative cooling of PVT panels addresses the short term, by extending their function to nighttime, during which no generation is taking place. Night radiative cooling utilizes the night sky as a heat sink through radiation heat transfer. This results in cooling of the working medium in solar devices. Hu et al. [121] demonstrated the potential of a solar thermal system in an experimental investigation, with favorable results. The concept can presumably be expanded to PVT collector technology.

Hydrogen is a form of energy storage that is gaining traction steadily in a variety of applications. One method of producing hydrogen is proton exchange membrane electrolysis, in which hydrogen is generated from water. The process consumes electrical energy and favors operational temperatures of up to 100 ° C, which can be provided by PVT. Studies have already explored this using water based PVT [122,123].

Table 8
PVT related parameters and recommendations.

Concept	Remark
LTH	Exploit Low Temp. Sources
HRV	Favorable Combination w/ LTH
Storage	Multiple forms available
Retrofitting	Old Building stock
Solar Cooling	Extend Operation
Radiative Cooling	No additional intervention needed
Hydrogen	Water based more suitable

In short, to enhance the PVT capabilities in building energy systems, various methods are available, depending on the circumstances of each application. An illustration presenting the concepts is given in Fig. 16 and remarks discussing the respective merits in Table 8.

4. Concluding remarks

A technical review concerning the state-of-the-art in Air based PVT technology and its integration with building energy systems was compiled, highlighting critical limitations in research. Specifically, the relatively lower system performance made air-based variants less attractive for applications, yet researchers are already initiating efforts to amend this. Concerning the methodology of experiments, a lack of unified approach was detected. This limits the comparability of results and effectiveness of new research. From the integration aspect, the full extent of applications has not been fully explored. Based on that, the following elements were proposed:

- A parallel between solar air heaters and Air based PVT technologies was drawn, emphasizing that methods employed for enhancing heat transfer in the former show potential for the latter as well. This has not been covered by literature sufficiently before. A description of heat transfer improvement techniques that are apt for PVT systems was given.
- Guidelines for the methodology in PVT investigations were provided. Standardized methods are vital for greater scientific impact. The aim is to streamline the experimental process in order to accelerate the dissemination of PVT research.
- Insights on the aspect of energy integration were presented, with the intent of introducing more strategies for the utilization of generated energy. Demonstrations of new integration applications will posi-

tively affect their outreach. Directions for future exploration were given as well.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Giorgos Aspetakis: Conceptualization, Methodology, Writing – original draft. **Qian Wang:** Supervision, Writing – review & editing.

Acknowledgement

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

References

[1] IEA, Buildings, Technical Report, IEA, Paris, 2022. https://www.iea.org/reports/buildings
[2] E. Commission, A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives (2020) 26.
[3] E. Commission, Nearly zero-energy buildings, Technical Report, 2021. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-buildings
[4] X. Zhu, X. Zhang, P. Gong, Y. Li, J. Build. Eng. 73 (2023) 106735, doi:10.1016/J.JOBE.2023.106735.
[5] IEA, Energy Policies of IEA Countries: Sweden 2019 Review, Technical Report, IEA, Paris, 2019. https://www.iea.org/reports/energy-policies-of-iea-countries-sweden-2019-review
[6] E. Lorenzo, G. Araujo, A. Cuevas, M. Egido, J. Minano, R. Zilles (1994) 316.
[7] E. Elibol, O.T. Özmen, N. Tutkun, O. Köysal, Renew. Sustain. Energy Rev. 67 (2017) 651–661, doi:10.1016/J.RSER.2016.09.051.
[8] J.K. Kaldellis, M. Kapsali, K.A. Kavadias, Renew. Energy 66 (2014) 612–624, doi:10.1016/J.RENENE.2013.12.041.
[9] K.E. Park, G.H. Kang, H.I. Kim, G.J. Yu, J.T. Kim, Energy 35 (2010) 2681–2687, doi:10.1016/J.ENERGY.2009.07.019.
[10] E. Skoplaki, J.A. Palyvos, Sol. Energy 83 (2009) 614–624, doi:10.1016/J.SOLENER.2008.10.008.
[11] K. Nishioka, T. Hatayama, Y. Uraoka, T. Fuyuki, R. Hagihara, M. Watanabe, Sol. Energy Mater. Sol. Cells 75 (3) (2003) 665–671, doi:10.1016/S0927-0248(02)00148-4. PVSEC 12, PART III
[12] P. Dwivedi, K. Sudhakar, A. Soni, E. Solomin, I. Kirpichnikova, Case Stud. Therm. Eng. 21 (2020), doi:10.1016/j.csite.2020.100674.
[13] J. Siecker, K. Kusakana, B.P. Numbi, Renew. Sustain. Energy Rev. 79 (2017) 192–203, doi:10.1016/J.RSER.2017.05.053.
[14] Y. Chaibi, T.E. Rhafiki, R. Simón-Allué, I. Guedea, S.C. Luaces, O.C. Gajate, T. Kousksou, Y. Zeraouli, J. Clean. Prod. 295 (2021) 126211, doi:10.1016/J.JCLEPRO.2021.126211.
[15] S.M. Sultan, M.N.E. Efzan, Sol. Energy 173 (2018) 939–954, doi:10.1016/J.SOLENER.2018.08.032.
[16] S. Diwania, S. Agrawal, A.S. Siddiqui, S. Singh, Int. J. Energy Environ. Eng. 11 (2020) 33–54, doi:10.1007/s40095-019-00327-y.
[17] Y. Tripanagnostopoulos, G. Huang, K. Wang, C.N. Markides, Ref. Module Earth Syst. Environ. Sci. (2021), doi:10.1016/B978-0-12-819727-1.00051-0.
[18] A. Pugsley, A. Zacharopoulos, J.D. Mondol, M. Smyth, Sol. Energy 207 (2020) 317–335, doi:10.1016/j.solener.2020.06.025.
[19] H.M. Maghrabie, K. Elsaid, E.T. Sayed, M.A. Abdelkareem, T. Wilberforce, A.G. Olabi, Sustain. Energy Technol. Assess. 45 (2021) 101151, doi:10.1016/J.SETA.2021.101151.
[20] G. Yu, H. Yang, Z. Yan, M.K. Ansah, Appl. Therm. Eng. 182 (2021), doi:10.1016/j.applthermaleng.2020.116081.
[21] T. Yang, A.K. Athienitis, Renew. Sustain. Energy Rev. 66 (2016) 886–912, doi:10.1016/J.RSER.2016.07.011.
[22] M. Chandrasekar, T. Senthilkumar, J. Clean. Prod. 322 (2021) 128997, doi:10.1016/J.JCLEPRO.2021.128997.
[23] X. Zhang, X. Zhao, S. Smith, J. Xu, X. Yu, Renew. Sustain. Energy Rev. 16 (2012) 599–617, doi:10.1016/J.RSER.2011.08.026.
[24] F. Hussain, M.Y.H. Othman, K. Sopian, B. Yatim, H. Ruslan, H. Othman (2013). 10.1016/j.rser.2013.04.014
[25] E.D. Rounis, A. Athienitis, T. Stathopoulos, Renew. Energy 163 (2021) 1729–1753, doi:10.1016/j.renene.2020.10.085.
[26] G. Asefi, A. Habibollahzade, T. Ma, E. Houshfar, R. Wang, Sol. Energy 216 (2021) 188–210, doi:10.1016/J.SOLENER.2021.01.005.
[27] T.T. Chow, G.N. Tiwari, C. Menezo, et al., Int. J. Photoenergy 2012 (2012), doi:10.1155/2012/307287.
[28] B. Agrawal, G.N. Tiwari, Energy Build. 42 (2010) 1472–1481, doi:10.1016/J.ENBUILD.2010.03.017.
[29] D. Vittorini, R. Cipollone, Energy 167 (2019) 159–167, doi:10.1016/J.ENERGY.2018.11.001.
[30] J.C. Mojumder, W.T. Chong, H.C. Ong, K.Y. Leong, Abdullah-Al-Mamoon, Energy Build. 130 (2016) 272–285, doi:10.1016/J.ENBUILD.2016.08.040.
[31] S. Benzarti, M. Chaabane, H. Mhiri, P. Bournot, J. Build. Eng. 53 (2022) 104553, doi:10.1016/J.JOBE.2022.104553.
[32] R. Kumar, M.A. Rosen, Appl. Therm. Eng. 31 (2011) 1402–1410, doi:10.1016/J.APPLTHERMALENG.2010.12.037.
[33] G. Barone, A. Buonomano, C. Forzano, A. Palombo, O. Panagopoulos, Energy Convers. Manage. 195 (2019) 1079–1097, doi:10.1016/J.ENCONMAN.2019.04.082.
[34] A. Sharma, R. Kumar, C.S. Rajoria, S. Suhag, P. Verma, O.D. Samuel, T.N. Verma, G. Dwivedi, in: Advancement in Materials, Manufacturing and Energy Engineering, Vol. II, Springer Nature Singapore, Singapore, 2022, pp. 361–373.
[35] B. Nghana, F. Tariku, G. Bitsuamlak, Energies 16 (14) (2023), doi:10.3390/en16145266.
[36] J.-H. Kim, J.-S. Yu, E. Gaucher-Loksts, B. Roy, V. Delisle, J.-T. Kim, Energies 15 (10) (2022), doi:10.3390/en15103779.
[37] M.E.A. Slimani, M. Amirat, I. Kurucz, S. Bahria, A. Hamidat, W.B. Chaouch, Energy Convers. Manage. 133 (2017) 458–476, doi:10.1016/J.ENCONMAN.2016.10.066.
[38] A. Chialastri, M. Isaacson, Energy Build. 150 (2017) 200–210, doi:10.1016/J.ENBUILD.2017.05.064.
[39] W. Fan, G. Kokogiannakis, Z. Ma, Sol. Energy 163 (2018) 315–328, doi:10.1016/J.SOLENER.2018.02.014.
[40] C. Lamnatou, J.D. Mondol, D. Chemisana, C. Maurer, Renew. Sustain. Energy Rev. 45 (2015) 36–51, doi:10.1016/J.RSER.2015.01.024.
[41] M. Debbarma, K. Sudhakar, P. Baredar, Renew. Sustain. Energy Rev. 73 (2017) 1276–1288, doi:10.1016/J.RSER.2017.02.035.
[42] W.H. McAdams, Heat Transmission, 3rd, McGraw-Hill, New York, 1954.
[43] J. Watmuff, W. Charters, D. Proctor, Coop. Mediterraneenne pour l'Energie Solaire -1 (1977) 56.
[44] J.S. Yu, J.H. Kim, J.T. Kim, Energies 2019, Vol. 12, Page 3120 12 (2019) 3120, doi:10.3390/EN12163120.
[45] S. Li, P. Karava, E. Savory, W.E. Lin, Sol. Energy 91 (2013) 297–315, doi:10.1016/J.SOLENER.2013.01.028.
[46] Y.J. Kim, K.S. Lee, L. Yang, E. Entchev, E.C. Kang, E.J. Lee, Energies 2020, Vol. 13, Page 1990 13 (2020) 1990, doi:10.3390/EN13081990.
[47] Y.J. Kim, K. Kim, E.J. lee, E.C. Kang, J. Therm. Anal. Calorim. (2023) 1–15, doi:10.1007/S10973-023-12410-Y/FIGURES/23.
[48] A. Shrivastava, J.P.A. Jose, Y.D. Borole, R. Saravanakumar, M. Sharifpur, H. Harasi, R.K.A. Razak, A. Afzal, Sustain. Energy Technol. Assess. 49 (2022) 101782, doi:10.1016/J.SETA.2021.101782.
[49] J.G. Hernandez-Perez, J.G. Carrillo, A. Bassam, M. Flota-Banuelos, L.D. Patino-Lopez, Appl. Therm. Eng. 184 (2021) 116238, doi:10.1016/J.APPLTHERMALENG.2020.116238.
[50] Z. Arifin, D.D.D.P. Tjahjana, S. Hadi, R.A. Rachmanto, G. Setyohandoko, B. Sutanto, Int. J. Photoenergy 2020 (2020), doi:10.1155/2020/1574274.
[51] G. Ömeroğlu, Int. J. Photoenergy 2018 (2018), doi:10.1155/2018/9139683.
[52] D. Roeleveld, G. Hailu, A.S. Fung, D. Naylor, T. Yang, A.K. Athienitis, Energy Procedia 78 (2015) 1901–1906, doi:10.1016/J.EGYPRO.2015.11.359.
[53] E. Kaplani, S. Kaplanis, Sol. Energy 107 (2014) 443–460, doi:10.1016/J.SOLENER.2014.05.037.
[54] Y.B. Assoa, F. Sauzedde, B. Boillot, Renew. Energy 129 (2018) 121–131, doi:10.1016/J.RENENE.2018.05.102.
[55] O. Zogou, H. Stapountzis, Appl. Energy 88 (2011) 853–866, doi:10.1016/J.APENERGY.2010.08.023.
[56] K. Bot, L. Aelenei, H. Gonçalves, M.d.G. Gomes, C.S. Silva, Energies 2021, Vol. 14, Page 2191 14 (2021) 2191, doi:10.3390/EN14082191.
[57] S.M. Kim, J.H. Kim, J.T. Kim, Energies 2019, Vol. 12, Page 2661 12 (2019) 2661, doi:10.3390/EN12142661.
[58] R.A. Agathokleous, S.A. Kalogirou, S. Karellas, Renew. Energy 128 (2018) 541–552, doi:10.1016/J.RENENE.2017.06.085.
[59] N. Choubineh, H. Jannesari, A. Kasaeian, Renew. Sustain. Energy Rev. 101 (2019) 103–111, doi:10.1016/J.RSER.2018.11.001.
[60] A. Guideline, et al., ASHRAE Guidel 4 (2014) 1–150.
[61] S. Agrawal, A. Tiwari, Sol. Energy 85 (2011) 3046–3056, doi:10.1016/J.SOLENER.2011.09.003.
[62] S.C. Solanki, S. Dubey, A. Tiwari, Appl. Energy 86 (2009) 2421–2428, doi:10.1016/J.APENERGY.2009.03.013.
[63] S. Golzari, A. Kasaeian, M. Amidpour, S. Nasirivatan, S. Mousavi, Renew. Energy 127 (2018) 284–297, doi:10.1016/J.RENENE.2018.04.029.
[64] A. Fudholi, M. Zohri, N.S.B. Rukman, N.S. Nazri, M. Mustapha, C.H. Yen, M. Mohammad, K. Sopian, Renew. Sustain. Energy Rev. 100 (2019) 44–51, doi:10.1016/j.rser.2018.10.019.
[65] ISO 9806:2017 Solar energy – Solar thermal collectors – Test methodsTechnical Report, International Organization for Standardization, Geneva, Switzerland, 2017. https://www.iso.org/standard/67978.html
[66] P. Ooshaksaraei, K. Sopian, S.H. Zaidi, R. Zulkifli, Renew. Energy 102 (2017) 279–293, doi:10.1016/J.RENENE.2016.10.043.
[67] E. Bigaila, E. Rounis, P. Luk, A. Athienitis, Energy Procedia 78 (2015) 1931–1936, doi:10.1016/J.EGYPRO.2015.11.374.
[68] E.D. Rounis, Z. Ioannidis, A.M. Sigounis, A. Athienitis, T. Stathopoulos, Sol. Energy 232 (2022) 328–343, doi:10.1016/J.SOLENER.2021.12.058.
[69] W. Lin, Z. Ma, H. Ren, S. Gschwander, S. Wang, Renew. Energy 130 (2019) 1116–1129, doi:10.1016/J.RENENE.2018.08.071.
[70] Y. Chen, A.K. Athienitis, K. Galal, Sol. Energy 84 (2010) 1892–1907, doi:10.1016/J.SOLENER.2010.06.013.

[71] R. Kamel, N. Ekrami, P. Dash, A. Fung, G. Hailu, Energy Procedia 78 (2015) 424–429, doi:10.1016/J.EGYPRO.2015.11.687.
[72] J. Bambara (2012).
[73] L. Ma, H. Ge, L. Wang, L. Wang, Build. Simul. 14 (2021) 1467–1486, doi:10.1007/s12273-021-0763-1.
[74] E. Bigaila, A.K. Athienitis, Energy Build. 149 (2017) 298–309, doi:10.1016/J.ENBUILD.2017.05.045.
[75] J. Hasan, A.S. Fung, M. Horvat, J. Build. Eng. 44 (2021) 103325, doi:10.1016/J.JOBE.2021.103325.
[76] C. Lamnatou, G. Notton, D. Chemisana, C. Cristofari, Sci. Total Environ. 699 (2020) 134269, doi:10.1016/J.SCITOTENV.2019.134269.
[77] T. Brahim, A. Jemni, Sol. Energy 153 (2017) 540–561, doi:10.1016/J.SOLENER.2017.05.081.
[78] A.H.A. Al-Waeli, H.A. Kazem, M.T. Chaichan, K. Sopian, Photovoltaic/thermal (PV/t) systems: Principles, design, and applications, 2019.
[79] T.E. Kuhn, C. Erban, M. Heinrich, J. Eisenlohr, F. Ensslen, D.H. Neuhaus, Energy Build. 231 (2021) 110381, doi:10.1016/J.ENBUILD.2020.110381.
[80] T. Salameh, D. Zhang, A. Juaidi, A.H. Alami, I. Al-Hinti, A.G. Olabi, J. Clean. Prod. 326 (2021) 129421, doi:10.1016/J.JCLEPRO.2021.129421.
[81] M. Ahmed-Dahmane, A. Malek, T. Zitoun, Energy Convers. Manage. 175 (2018) 49–66, doi:10.1016/J.ENCONMAN.2018.08.090.
[82] A.-M. Sigounis, C. Vallianos, A. Athienitis, Renew. Energy 212 (2023) 655–668, doi:10.1016/j.renene.2023.05.059.
[83] Y.D. Khimsuriya, D.K. Patel, Z. Said, H. Panchal, M.M. Jaber, L. Natrayan, V. Patel, A.S. El-Shafay, Appl. Therm. Eng. 214 (2022) 118817, doi:10.1016/J.APPLTHERMALENG.2022.118817.
[84] S. Rashidi, M.H. Kashefi, F. Hormozi, Sol. Energy 171 (2018) 929–952, doi:10.1016/J.SOLENER.2018.07.017.
[85] P. Promvonge, S. Skullong, Int. J. Heat Mass Transf. 172 (2021) 121220, doi:10.1016/J.IJHEATMASSTRANSFER.2021.121220.
[86] S.B. Bopche, M.S. Tandale, Int. J. Heat Mass Transf. 52 (2009) 2834–2848, doi:10.1016/J.IJHEATMASSTRANSFER.2008.09.039.
[87] P. Sriromreun, C. Thianpong, P. Promvonge, Int. Commun. Heat Mass Transf. 39 (2012) 945–952, doi:10.1016/J.ICHEATMASSTRANSFER.2012.05.016.
[88] H. Parsa, M. Saffar-Avval, M.R. Hajmohammadi, Int. J. Mech. Sci. 205 (2021) 106607, doi:10.1016/J.IJMECSCI.2021.106607.
[89] S. Tamna, S. Skullong, C. Thianpong, P. Promvonge, Sol. Energy 110 (2014) 720–735, doi:10.1016/J.SOLENER.2014.10.020.
[90] H.E. Fawaz, M.T.S. Badawy, M.F.A. Rabbo, A. Elfeky, Alexandria Eng. J. 57 (2018) 633–642, doi:10.1016/J.AEJ.2017.02.020.
[91] R. Kumar, M. Sethi, R. Chauhan, A. Kumar, Renew. Energy 101 (2017) 856–872, doi:10.1016/J.RENENE.2016.09.033.
[92] S. Eiamsa-ard, A. Suksangpanomrung, P. Promthaisong, Int. J. Therm. Sci. 177 (2022) 107577, doi:10.1016/J.IJTHERMALSCI.2022.107577.
[93] N. Depaiwa, T. Chompookham, P. Promvonge, Proceedings of the International Conference on Energy and Sustainable Development: Issues and Strategies, ESD 2010 (2010), doi:10.1109/ESD.2010.5598864.
[94] H. Xiao, Z. Dong, Z. Liu, W. Liu, Appl. Therm. Eng. 179 (2020) 115484, doi:10.1016/J.APPLTHERMALENG.2020.115484.
[95] G. Zhou, Q. Ye, Appl. Therm. Eng. 37 (2012) 241–248, doi:10.1016/J.APPLTHERMALENG.2011.11.024.
[96] P.J. Bezbaruah, R.S. Das, B.K. Sarkar, Renew. Energy 180 (2021) 109–131, doi:10.1016/J.RENENE.2021.08.046.
[97] J.S. Sawhney, R. Maithani, S. Chamoli, Appl. Therm. Eng. 117 (2017) 740–751, doi:10.1016/J.APPLTHERMALENG.2017.01.113.
[98] M.T. Baissi, A. Brima, K. Aoues, R. Khanniche, N. Moummi, Appl. Therm. Eng. 165 (2020) 113563, doi:10.1016/J.APPLTHERMALENG.2019.03.134.
[99] S. Skullong, P. Promthaisong, P. Promvonge, C. Thianpong, M. Pimsarn, Sol. Energy 170 (2018) 1101–1117, doi:10.1016/J.SOLENER.2018.05.093.
[100] S. Skullong, P. Promvonge, C. Thianpong, N. Jayranaiwachira, M. Pimsarn, Appl Therm Eng 122 (2017) 268–284, doi:10.1016/J.APPLTHERMALENG.2017.04.158.
[101] Z. Zhao, L. Luo, D. Qiu, Z. Wang, B. Sundén, Energy 224 (2021) 119944, doi:10.1016/J.ENERGY.2021.119944.
[102] D.J. Dezan, A.D. Rocha, W.G. Ferreira, Appl. Energy 263 (2020) 114556, doi:10.1016/J.APENERGY.2020.114556.
[103] T.T. Ngo, N.M. Phu, J. Therm. Anal. Calorim. 139 (2020) 3235–3246, doi:10.1007/s10973-019-08709-4.
[104] N.S. Deo, S. Chander, J.S. Saini, Renew. Energy 91 (2016) 484–500, doi:10.1016/J.RENENE.2016.01.067.
[105] V.S. Hans, R.S. Gill, S. Singh, Exp. Therm. Fluid Sci. 80 (2017) 77–89, doi:10.1016/J.EXPTHERMFLUSCI.2016.07.022.
[106] R.S. Gill, V.S. Hans, R.P. Singh, Appl. Therm. Eng. 191 (2021) 116871, doi:10.1016/J.APPLTHERMALENG.2021.116871.
[107] I. Singh, S. Singh, Sol. Energy 162 (2018) 442–453, doi:10.1016/J.SOLENER.2018.01.019.
[108] R.K. Nayak, S.N. Singh, Sol. Energy 137 (2016) 434–440, doi:10.1016/J.SOLENER.2016.08.024.
[109] N. Kumar, A. Kumar, R. Maithani, Therm. Sci. Eng. Progr. 17 (2020) 100493, doi:10.1016/J.TSEP.2020.100493.
[110] EN 12975:2022 Solar collectors. General requirementsTechnical Report, EUROPEAN COMMITTEE FOR STANDARDIZATION, 2022.
[111] M. Tawfik, X. Tonnellier, C. Sansom, Renew. Sustain. Energy Rev. 90 (2018) 802–813, doi:10.1016/J.RSER.2018.03.059.
[112] V. Esen, S. Sağlam, B. Oral, Renew. Sustain. Energy Rev. 77 (2017) 1240–1250, doi:10.1016/J.RSER.2017.03.062.
[113] G. Leary, G. Switzer, G. Kuntz, T. Kaiser, Conference Record of the IEEE Photovoltaic Specialists Conference 2016-November (2016) 3062–3067, doi:10.1109/PVSC.2016.7750227.
[114] IEC 60904-9:2020 Photovoltaic devices - Part 9: Classification of solar simulator characteristicsTechnical Report, International Electrotechnical Commission, 2020. https://webstore.iec.ch/publication/28973
[115] H. Pieskä, C. Wang, B. Nourozi, A. Ploskić, Q. Wang, J. Build. Eng. 56 (2022) 104738, doi:10.1016/J.JOBE.2022.104738.
[116] J.G. Ahn, J.H. Kim, J.T. Kim, Energy Procedia 78 (2015) 3007–3012, doi:10.1016/J.EGYPRO.2015.11.705.
[117] Q. Wang, A. Ploskić, X. Song, S. Holmberg, Energy Build. 121 (2016) 250–264, doi:10.1016/J.ENBUILD.2016.02.050.
[118] A. Miglioli, N. Aste, C.D. Pero, F. Leonforte, Energy Built Environ. (2021), doi:10.1016/J.ENBENV.2021.07.002.
[119] E. Saretta, P. Caputo, F. Frontini, Sustain. Cities Soc. 44 (2019) 343–355, doi:10.1016/J.SCS.2018.10.002.
[120] J. Guo, S. Lin, J.I. Bilbao, S.D. White, A.B. Sproul, Renew. Sustain. Energy Rev. 67 (2017) 1–14, doi:10.1016/J.RSER.2016.08.056.
[121] M. Hu, B. Zhao, Suhendri, J. Cao, Q. Wang, S. Riffat, Y. Su, G. Pei, Energy 251 (2022) 123986, doi:10.1016/J.ENERGY.2022.123986.
[122] A. Salari, A. Hakkaki-Fard, A. Jalalidil, Int. J. Hydrogen Energy 47 (2022) 4472–4488, doi:10.1016/J.IJHYDENE.2021.11.100.
[123] H. Wang, W. Li, T. Liu, X. Liu, X. Hu, Energy Convers. Manage. 183 (2019) 97–108, doi:10.1016/J.ENCONMAN.2018.12.106.