



HAL
open science

Assessing the energy performance of solar photovoltaic, thermal and hybrid PVT panels in a building context: A systematic study of the criteria' definitions and studies parameters

Hafsa Fares, Nolwenn Le Pierrès, David Cheze, Etienne Wurtz

► To cite this version:

Hafsa Fares, Nolwenn Le Pierrès, David Cheze, Etienne Wurtz. Assessing the energy performance of solar photovoltaic, thermal and hybrid PVT panels in a building context: A systematic study of the criteria' definitions and studies parameters. *Solar Energy*, 2025, 286, pp.113126. 10.1016/j.solener.2024.113126 . cea-04880556

HAL Id: cea-04880556

<https://cea.hal.science/cea-04880556v1>

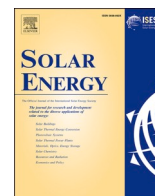
Submitted on 13 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



Assessing the energy performance of solar photovoltaic, thermal and hybrid PVT panels in a building context: A systematic study of the criteria' definitions and studies parameters

Hafsa Fares^{a,b}, Nolwenn Le Pierrès^{a,*}, David Chèze^b, Etienne Wurtz^b

^a Laboratoire procédés énergie bâtiment (LOCIE)-CNRS: UMR5271, Université Savoie Mont Blanc – Savoie Technolac, Le Bourget du Lac 73376, France

^b Univ. Grenoble Alpes – CEA, LITEN, INES, Le Bourget du Lac 73375, France

ARTICLE INFO

Keywords:

Photovoltaic
Solar thermal
Hybrid PVT
Energy performance indicators
Building

ABSTRACT

This study presents a comprehensive analysis of 30 research papers that define criteria for evaluating the energy performance of photovoltaic (PV), solar thermal (ST), and hybrid photovoltaic-thermal (PVT) panels in building integration. A key focus is the simultaneous evaluation of both heat and electricity production, which is a crucial challenge in comparing these technologies. The papers are categorized into four key metrics for combining energy forms: energy, primary energy, exergy, and energy equivalence. Among these, primary energy is the most frequently used, as it converts electricity to heat through location-specific primary energy factors, providing a common way to measure both energy types. Exergy, utilizing the second law of thermodynamics, allows for a more refined assessment by considering the quality of energy forms, unlike the first law which treats all energy as equal. However, variations in exergy analysis can arise due to differences in how studies account for the exergy of incident solar radiation and the chosen reference temperature. Energy equivalence, finally, considers the specific HVAC systems used together with solar panels. Additionally, this study identifies parameters that are frequently highlighted in solar panel comparisons. The highlights of this work provide a nuanced understanding of how PV, ST, and PVT technologies perform under various evaluation criteria, offering clearer guidance for future research and practical applications.

Nomenclature

Acronyms

BIPV	Building integrated photovoltaic
BIPVT	Building integrated photovoltaic thermal
BIST	Building integrated solar thermal
CCHP	Combined cooling, heating and power
COP	Coefficient of performance
CSHPSS	centralized solar heating plant with seasonal storage
CSP	Concentrated solar power
DHW	Domestic hot water
EMS	Energy management system
ER	Energy ratio
GHG	greenhouse gas
GSHP	Ground source heat pump
HP	Heat pump
HVAC	heating, ventilation, and air conditioning
IEA	International Energy Agency
LCF	Load cover factor

(continued on next column)

Nomenclature (continued)

MCPVT	Micro channel photovoltaic thermal
MCST	Micro channel solar thermal
OPVETC	Open Loop Photovoltaic Evacuated Tube Collector
PES	Primary energy saving
PESR	Primary energy saving ratio
PV	Photovoltaic
PVT	Photovoltaic thermal
SCF	Supply cover factor
SCR	Self-consumption ratio
SCR	Self-consumption ratio
SF	Solar fraction
SSR	Self-sufficiency ratio
ST	Solar thermal
TES	Thermal energy storage

Variables (Greek symbols)

$\eta_{\text{electrical}}$	Electrical instantaneous efficiency
$\eta_{\text{primaryenergy}}$	Primary energy efficiency

(continued on next page)

* Corresponding author.

E-mail address: Nolwenn.le-pierres@univ-smb.fr (N. Le Pierrès).

<https://doi.org/10.1016/j.solener.2024.113126>

Received 26 July 2024; Received in revised form 13 November 2024; Accepted 16 November 2024

Available online 11 December 2024

0038-092X/© 2024 The Author(s). Published by Elsevier Ltd on behalf of International Solar Energy Society. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Nomenclature (continued)

η_{solar}	Overall energy efficiency of a solar panel
η_{thermal}	Thermal efficiency
η_{Tpower}	Primary energy conversion factor
$\bar{\eta}$	energy efficiency over a given time period
ϕ_{solar}	Overall exergy efficiency of a solar panel
Variables (Latin symbols)	
A	Area of the solar panel in m^2
c_p	Specific heat capacity in $\text{J.K}^{-1}.\text{kg}^{-1}$
E_{pv}	Electricity produced by PV or PVT panels over a time period in J
E_{thermal}	Heat produced by ST or PVT collectors over a time period in J
\dot{E}_{pv}	Electrical power produced by PV panels in W
$EX_{\text{electrical}}$	Electrical exergy in J
EX_{in}	Exergy input in J
EX_{loss}	Exergy loss in J
EX_{out}	Exergy output in J
EX_{sun}	Exergy of global solar radiation in J
EX_{thermal}	Thermal exergy in J
G_{sol}	Global solar radiation received by the collectors over a time period in J/m^2
\dot{G}_{sol}	Global solar irradiance received by the collectors in W/m^2
I_r	Irreversibilities of a transformation in J
M	Solar heated water mass in kg
\dot{m}	mass flow rate of heat transfer fluid in the collectors in kg/s
T_0	Reference temperature for exergy analysis in K
T_a	Ambient temperature in K
T_{cell}	PV cell temperature in K
T_{in}	Fluid inlet temperature in the ST collector in K
T_{out}	Fluid outlet temperature in the ST collector in K
T_{sun}	Sun temperature in K

1. Introduction

The building sector accounts for 36 % of global energy use and 40 % of CO₂ emissions, as reported by the International Energy Agency [1]. These emissions stem not only from the construction phase of buildings but also from their operational phase [2]. Addressing these emissions presents a significant opportunity for reducing environmental impact. In addition to building renovations and changes in energy consumption habits, integrating renewable energy sources is crucial for mitigating greenhouse gas (GHG) emissions during the operational phase of buildings.

Active solar panels, including photovoltaic (PV), solar thermal (ST), and hybrid photovoltaic thermal (PVT) systems, provide versatile solutions for meeting building energy needs. PV systems convert sunlight into electricity, addressing the growing global demand for power, which is projected to increase by 30 % by 2030 [3]. ST systems harness solar energy for space heating and hot water production, which constitute approximately 47 % of residential energy consumption. Hybrid PVT systems combine both thermal and electrical energy, presenting a comprehensive approach to achieving energy independence and reducing reliance on conventional power sources. Unlike concentrated solar power (CSP) technology, which is primarily used for large-scale power generation, PV, ST, and PVT systems are more applicable to residential and commercial buildings. Solar technologies are foreseen to play a major share in the net-zero emissions scenario [4].

Integrating PV, ST, and PVT systems into building applications presents several challenges. They are related to standards and regulations, system choices and positioning, health and safety considerations, system weight, and unit size as well as shading issues in urban context, building barriers, and historical, and architectural constraints, as detailed in Gholami et al. [5]. Furthermore, each technology produces different forms of energy, which complicates direct comparison and integration. The development of PVT technology has particularly emphasized the need for new methods to consider both heat and electricity effectively. For instance, Ahmedinejad et al. [6] or Assareh et al. [7] investigated PVT panels using criteria incorporating both forms of energy.

Balancing solar heat and electricity production outputs and optimizing their use within a building requires a thorough understanding of

each technology's performance characteristics. Moreover, the intermittent nature of solar energy adds complexity to the integration process consisting of coupling the solar technologies to auxiliary systems. Ensuring a consistent and reliable energy supply while maximizing the use of self-generated solar energy involves addressing issues related to energy storage, demand management, grid interaction and system efficiency. The ability to integrate these technologies into diverse building contexts and climates further highlights the importance of developing robust evaluation criteria. Fig. 1 displays all these aspects. Therefore, this paper aims to systematically analyze the literature on the integration of PV, ST, and PVT systems together in buildings. The specific objectives of the study are:

1. To evaluate how existing research compares the energy performance of PV, ST, and PVT technologies through a systematic review analysis.
2. To provide a comprehensive summary of criteria combining both heat and electricity used for evaluating solar technologies.

By synthesizing and critically assessing the available research, this study seeks to offer valuable insights for researchers, practitioners, and policymakers involved in the integration of solar technologies in building applications.

2. Methodology

A systematic review involves a structured and comprehensive approach to gathering, evaluating, and synthesizing existing work on a specific research question. This work's analysis followed the approach outlined by Mengist et al. [9] that follows: identification, screening, eligibility, inclusion, and categorization, facilitating the organized collection and identification of relevant scientific records for analysis.

In this section, the scope of the study defined by the research question will be described, along with all other phases, to address the hypothesis that guided the selection of the final number of papers to be analyzed. Fig. 2 synthesizes the process.

2.1. Methodology: Scope of the study and identification phase

The scientific question that this literature analysis seeks to answer is: *How are the three solar technologies in a building integration context compared to one another in an energy performance perspective?*

This question allows to identify three branches that constitute the strings of the search. The first one concerns the solar energy systems, including the main possible name formulations for the three solar technologies. The second one concerns the building environment to limit the studies to this application, and finally the third string concerns the type of analysis that aims to assess the energy performance and compare the three technologies. The decision to include all the three solar technologies systematically, mainly the PVT collectors that produce both heat and electricity, is based on a desire to restrict the search to studies that include both forms of energies simultaneously. Table 1 shows the syntax used in both Web of Science and Scopus databases to retrieve the different references. Since the research domain of solar energy is constantly evolving and has made great strides in recent years, only the journal and conference papers published after 2010 were considered. This search was conducted last on the 4th of June 2024 and returned a total of 267 documents in the two databases jointly.

2.2. Methodology: Screening phase

The screening phase consisted first on putting aside 44 duplicates that appeared in the two databases, then skimming throughout the 223 left documents and selecting according to the title and abstract the relevant documents. The selection was conducted by excluding first the papers that are

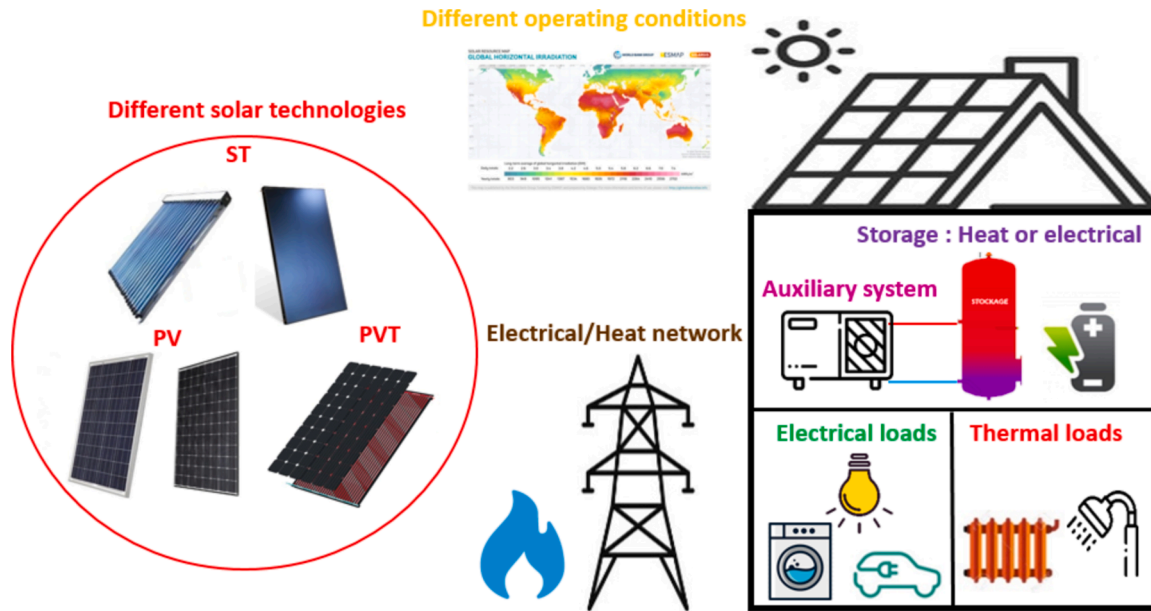


Fig. 1. Scope of the complexity of evaluating the solar technologies in a building context.

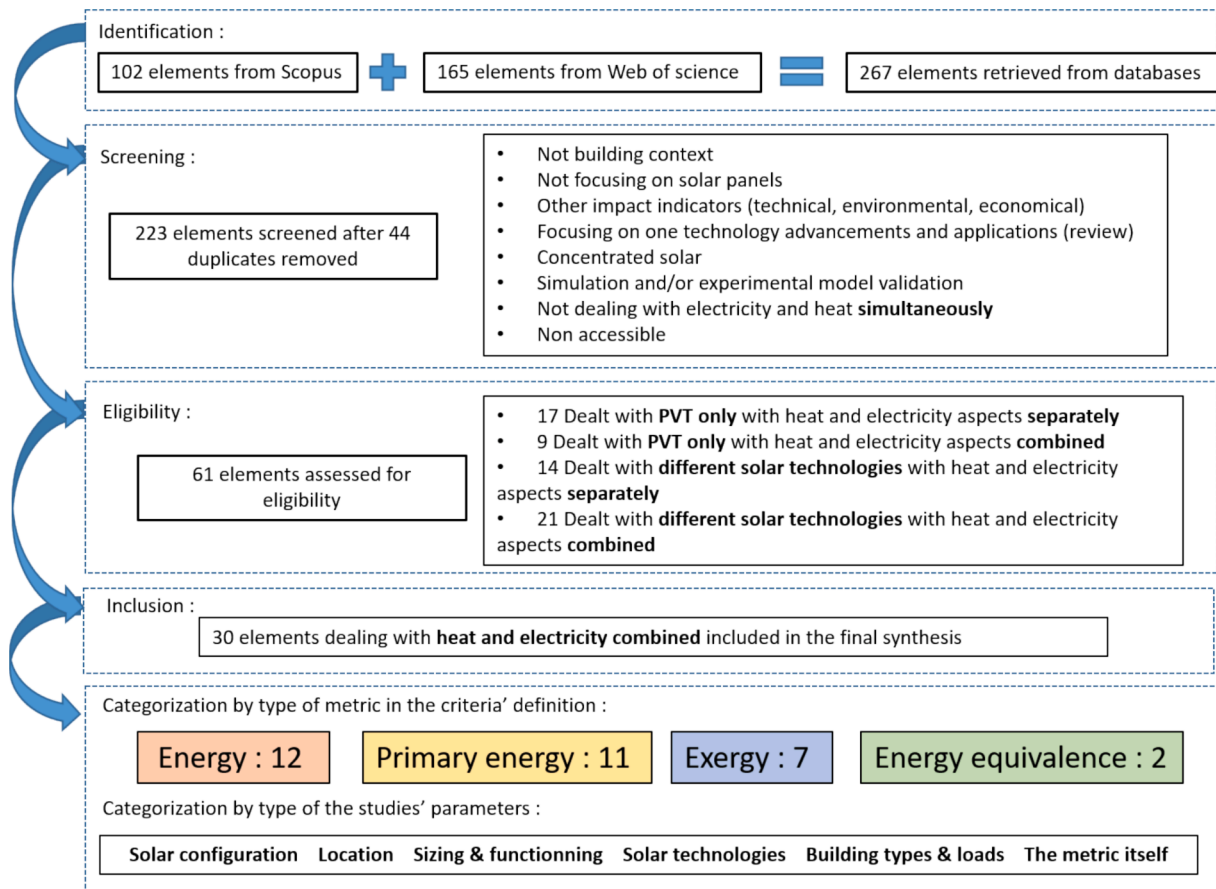


Fig. 2. Methodology of the systemic analysis.

- (i) not written in English,
- (ii) no more accessible and that are
- (iii) not in the building context, which represented small exceptions that still found their way into the search.

The papers:

- (iv) focusing more on other energy systems coupled with solar panels such as heat pump (HP) or boilers,

Table 1
Request on Web of science and Scopus for the identification phase.

Photovoltaic OR "PV" OR "BIPV"
AND
"PVT" OR "PV-T" OR "PV/T" OR (hybrid W/2 solar) OR "photovoltaic/thermal" OR "BIPVT"
AND
("Solar Thermal" OR "ST") W/2 (panel OR collector) OR "BIST"
AND
Building* OR house* OR dwelling*
AND
Comparative OR analysis OR comparison OR assessment OR study OR compar*

- (v) focusing on other impact indicators (technical, environmental, economic),
- (vi) focusing on one technology advancement and application,
- (vii) studying concentrated solar technology, and
- (viii) conducting simulation and/or experimental model validation,

were also discarded. But most importantly, the papers

- (ix) not dealing with electricity and heat simultaneously

were not of interest for the paper. At the end of this process, only 61 elements were assessed for the eligibility phase.

2.3. Methodology: Eligibility and inclusion phases

At this stage, all the documents dealt with heat and electricity, but only the ones combining both through the definition of indicators that include both forms of energies at once were of interest for this study. Throughout 61 papers, as the papers could be classified as shown in Fig. 3, only the 30 elements dealing with heat and electricity combined were included to the following step.

In the following are a few examples from the 31 papers discarded in the eligibility phase that all defined heat and electricity separately in their energy performance indicators. Herrando et al. [10] analyzed hybrid PVT systems with 2 different solar fractions: one for heat and the other for electricity. Deymi-Dashtebayaz et al. [11] proposed a multi-generation system with PVT collectors, also using separate indicators for electricity and heat. Khordehghah et al. [12] tested a PVT system providing both electricity and hot water, but defined the energy performance of the system by evaluating the electricity and heat productions separately. Souliotis et al. [13] also evaluated heat and electricity separately. Wang et al. [14] demonstrated that PVT systems for combined heat and power production outperformed others, but by distinguishing between electrical and thermal energy in their performance indicators. Finally, Baur et al. [15] tested a hybrid solar thermal electric panel system, demonstrating a significant increase in thermal efficiency, although solar electric production was slightly reduced, with energy performance criteria divided between heat and electricity.

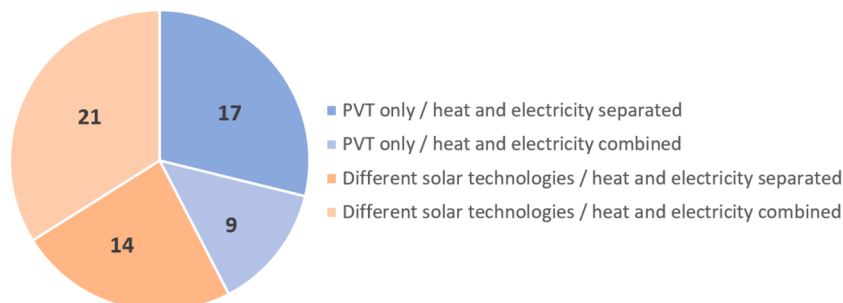


Fig. 3. Eligibility phase.

2.4. Methodology: Categorization phase

2.4.1. Categorization by metric in the criteria' definitions

At this stage, the 30 selected publications were categorized according to the type of metrics used to combine both heat and electricity in the criteria' definitions. Four categories were defined which are listed as shown in Fig. 4: energy, primary energy, exergy and energy equivalence. By using these categories, the analysis can better address the diverse ways in which energy is produced, utilized, and assessed across various studies, facilitating a clearer understanding of the relative performances of PV, ST, and PVT technologies. In Table 2 are given the general definitions of these metrics' categories. This categorization also allowed to organize the analysis of the publications in section 3.

2.4.2. By type of studies' parameters

Studies investigate many parameters to assess the performance of solar panels. Skimming through the papers allowed identifying similarities in the studies parameters interest. In Fig. 5 is displayed the distribution of the criteria types according to each parameter studied.

The initial request for the paper selection, as explained in Fig. 2, integrated both "photovoltaic" and "thermal" terms, which led to the inclusion of the 9 studies that only studied PVT collectors. These studies were not concerned by the solar configuration parameter study that is in the top recurrent parameters that consists in varying the solar panels types that are being studied, i.e. PV, ST and PVT. The studies focusing on changing the location (that influences the temperature and solar irradiance) where the solar panels are operating, is also in the top most recurrent parameter studies. At the same level are the study of different sizing and functioning of the solar systems (mainly by changing the number of collectors or the surface, but also by changing the sizing of storage or operating parameters such as water flow rate and inlet temperatures for solar thermal systems).

Parametric studies of different solar technologies by changing the technology of a same collector, for example comparing between different types of photovoltaic cells, and changing the building type or building loads by varying the building envelop or the building's energy needs, are less frequent. Finally, one study conducted a parametric study on the criterion type itself by testing different energy equivalence converting factors to convert heat to electricity. Fig. 4 also shows that, as a function of the aim of the study (that is to say the type of parameters that

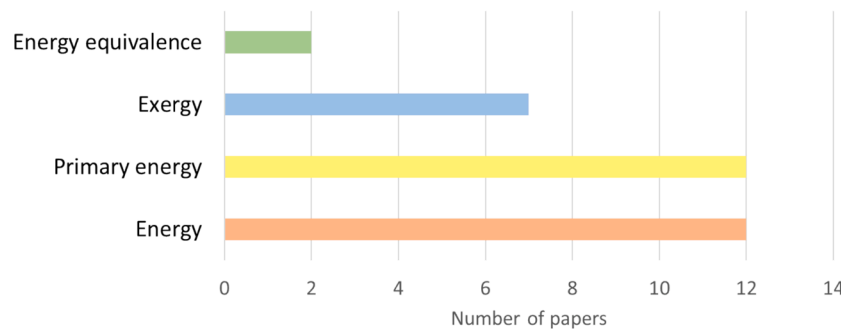


Fig. 4. Categorization of the papers by criteria' types.

Table 2
Definition of the four metrics identified to categorize the publications.

Metric categories	Description
Energy	Energy, expressed in Joule, is the capacity of a system to do work or produce a change. It exists in various forms, such as kinetic, potential, thermal, chemical, and others. The first law of thermodynamics states that energy cannot be created or destroyed, but only transformed from one form to another or transferred between systems. This conservation principle ensures that the total energy within an isolated system remains constant over time, with any changes being accounted for by heat transfer or work done.
Primary energy	Primary energy refers to energy sources that exist in nature before any human-made conversions, encompassing raw forms like fossil fuels, nuclear energy, and renewable sources. Its measurement reflects the total amount of energy contained within these natural resources, before any processing or refinement (Frischknecht et al. (2015)).
Exergy	Exergy, expressed in Joule, is a measure of the maximum useful work that can be obtained from a system as it interacts with its environment. It accounts for both the quantity and quality of energy within a system, considering factors such as temperature, pressure, and entropy. The second law of thermodynamics states that the total entropy of an isolated system always increases over time, or remains constant in ideal reversible processes. It implies that natural processes tend towards states of higher entropy, and thus there are limitations to the efficiency of energy conversion processes.
Energy equivalence	Energy equivalence refers to expressing energy quantities in terms of another energy source, such as converting energy from one form to another using conversion factors that are not primary energy factors.

are changed in a specific study), there is no obvious choice of criteria considered: all the criteria are distributed quite similarly in all kinds of parameters studies.

3. Publications analysis: Different criteria used for solar panels evaluation

This section describes the 30 studies that defined indicators mixing electricity and heat following the categorization described in section 2.4.1, starting with the energy metric followed by the primary energy form, exergy, and finally energy equivalence.

3.1. Energy criteria

In thermodynamics, the concept that allows combining different forms of energy is the First Law of Thermodynamics. In the following, the studies that combined the two forms of energy, ie. heat and electricity, without any conversion, to define criteria such as the total produced energy, energy efficiency, solar fractions of the solar systems, and so on, are discussed. In Table 3 are summarised all the criteria belonging to this energy category, encountered in the studies, with their definitions and the parametric studies in which they have been used.

3.1.1. Energy production/fuel savings

A first energy type criterion used to compare different solar technologies is the energy production. Gagliano et al. [16] compared PVT and conventional PV and ST plants used in a building, based on their total energy production. First, they compared the total energy output of PVT and PV for three different cities: Catania, Split, and Freiburg. For these cities with different solar radiations, the area allocated to solar

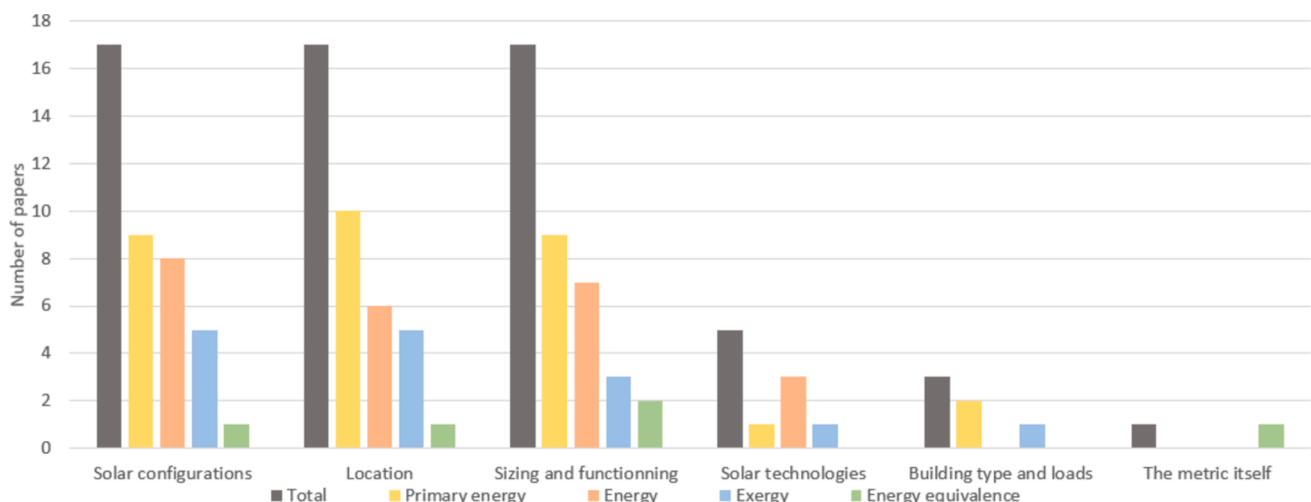


Fig. 5. Categorization of the papers by parameters' types.

Table 3
Definition of the energy type criteria identified in the publications.

Criteria	Reference	Parametric study	Definition	Main findings
Energy production	Gagliano et al. [16]	Location/Sizing	The effective total solar energy produced in a year by the PV (electricity), the ST (heat) and PVT (electricity and heat). For PVT panels, the useful thermal energy saving represents the actual contribution of the solar thermal system in reducing the energy produced by the back-up boiler necessary for DHW production. The thermal losses in the hydraulic components (pipes, solar tank and heat exchanger) are considered using such definition.	PVT panels produced 20–33 % more energy than PV panels across Catania, Split, and Freiburg. PVT panels produced 6–7 % more energy than the optimal 80 % PV + 20 % ST configuration across Catania, Split, and Freiburg.
Fuel saving	Dimri and Ramousse [17]	Sizing	Fuel saving represents the reduction resulting from the integration of renewable solar technologies, of the energy demands (comprising electricity, domestic hot water, and space heating) of building	PVT systems achieved 9–44 % more fuel savings than the other configurations (PV + SAHP, Grid + ST, PV + ST)
Energy efficiency	Abbas et al. [21]	–	The overall electrical and thermal efficiency of PVT and ST in series. \dot{G}_{sol} (Eq. (1)) is the incident solar irradiance, multiplied by the transmission coefficient of the glass top layer of the collector and the absorption coefficient of the absorber (or PV module)	The PVT-ST system demonstrated mean daily electrical, thermal, and overall energy efficiencies of 14.08 %, 60.12 %, and 74.20 %, respectively.
	Gagliano et al. [16]	Location/Sizing	Overall electrical and thermal efficiencies of the combination of PV + ST and the PVT panels. A (Eq. (1)) is the absorber surface. For ST panels \dot{G}_{sol} (Eq. (1)) is the incident solar irradiance, while for PVT panels, it is reduced by the amount of solar energy converted in the PV module into electrical energy.	The PV/T plant obtains the maximum performances with efficiencies of 19.1 %. The efficiency of the PV + ST plants do not exceed 17.8 %.
	Zhang et al. [22]	Location/Sizing/Solar technology/functioning	Overall energy efficiency of PVT (adding electricity and thermal efficiency).	The optimized PVT efficiency using spectral splitting with nanofluid achieved daily overall efficiencies of 47–58 % during the heating season across three Chinese cities.
	Maoulida et al. [23]	Location	Same as above.	PVT panels achieved a maximum overall efficiency of 40 % in France during one summer and maintained an annual overall performance of 40 % in the Comoros.
	Daghigh et al. [20]	Solar technology/functioning	Same as above.	BIPVT collectors achieved overall efficiencies of 71–76 % for amorphous silicon modules and 56–62.5 % for crystalline silicon modules under Malaysian meteorological conditions.
Solar fraction	Tripty and Nasrin [25]	Functioning	Overall energy efficiency of PVT (adding electricity and heat production). \dot{G}_{sol} (Eq. (1)) is the incident solar irradiance, multiplied by the transmission coefficient of the glass top layer of the collector and the absorption coefficient of the solar cell	The PVT solar panels achieved overall efficiencies between 61.5 % and 96.5 %, increasing with higher mass flow rates and lower inflow temperatures.
	Johnson et al. [24]	Functioning/Solar technology	Same as above. \dot{G}_{sol} (Eq. (1)) is the radiation on tilted surface of the collector.	The OPVETC solar panels achieved an annual overall energy efficiency of 66 %, compared to 53 % for the standard PVT system.
	Kashan et al. [26]	Sizing/Location	Solar fraction shows what percentage of the total required energy for DHW solar production can be provided by solar energy.	The average annual solar fractions are 18 % for PV-R, 75.7 % for MCST + HP, 70.3 % for flat-plate ST, and 76.4 % for MCPVT + HP.
Renewable energy fraction	Johnson et al. [24]	Functioning/Solar technology	Total load met from the solar source over the Total building energy demand. Also name 'self-sufficient ratio' (SSR)	Their novel PVT system recorded an annual overall solar fraction equal to 87 %.
	Rosato et al. [28]	Solar technology	The renewable energy fraction for the CSHPS is determined by calculating the ratio of energy (both thermal and electric) supplied by solar sources and/or wood pellets boiler compared to the total energy needs of the plant and buildings.	The system composed only of PV panels coupled to the wood pellet boiler and batteries, achieved a renewable energy fraction of 66.1 %.
Load cover factor	Rosato et al. [27]	Sizing	Same as above.	This time, the ratio achieves 96.8 % and is higher than the previous one, because the system combines both PV and ST collectors.
	Kim et al. [29]	Solar technology	Defined only for the PV panels, as the ratio between the used solar electricity generated by the PV systems and building loads, comprising either BIPV, ST or PVT.	The monthly average LCF values are displayed in Fig. 7 of Kim et al. [29]. The ST system case 3 exhibited higher LCF values than PV and PVT cases.
Solar self-consumption	Dimri and Ramousse [17]	Sizing	Also called solar self-production, defined as the ratio of total useful energy produced by solar panels to the total DHW, electrical and space heating building demand.	The case with PVT panels recorded the highest self-production rate.
	Dimri and Ramousse [17]	Sizing	It is the ratio of total useful energy produced by solar panels to the total energy produced by the solar panels.	The highest self-consumption was met by the PV and ST used together.
Net zero energy balance	Good et al. [30]	Solar technology	Defined as the difference between the annual energy exported by the building and delivered to the building by the external grid.	The lowest value was recorded by the PV solar configuration with a value equal to 2086 kWh annually.

installations was not the same: panels were sized to meet the same electricity needs, equal to 3000 kWh/year. The surface areas were therefore respectively: 11.8, 12.1 and 17.5 m². The total energy produced in a year by the PV panels is the electrical output of the PV collector obtained in the simulation results, and for the PVT collector, it is the sum of both the electrical and thermal outputs. The comparison reveals significant advantages for PVT, with the total energy production exceeding conventional PV by approximately 33 % and 20 % in Catania and Freiburg, respectively.

Secondly, a parametric study on the panels sizing is carried out to compare a conventional PV + ST panel configuration with a PVT installation, this time considering the heat output produced by the ST. Therefore, the analysis compares a PVT plant with PV + ST plants, examining various proportions of the available surface area occupied by ST and PV modules, for the same total areas detailed earlier (11.8, 12.1 and 17.5 m²). The results are given for the best PV + ST configuration composed of 80 % PV and 20 % ST, that produced 4385 kWh/year, but still lower than the energy produced by the PVT system (4795 kWh/year), in Catania. The same trend was observed for the other two cities: in Split, the 80 % PV + 20 % ST produced 4201 kWh/year versus 4489 kWh/year for the PVT, and in Freiburg, 3799 kWh/year and 4058 kWh/year, respectively. However, this analysis did not address the quality of thermal and electrical energy, that is discussed in the same paper and analysed using primary energy (as will be discussed in section 3.2.4).

Dimri and Ramousse [17] evaluated the performance of four different solar combined heating and power systems, namely PV with solar-assisted HP, national grid and ST panels, PV and ST panels together and PVT hybrid solar collector, and compared them to a conventional reference system (national grid and gas boiler), in a case study of an individual house in Chambéry. The fuel savings was defined as the total savings in kWh/y due to the incorporation of renewable solar technologies. In the reference case, it was zero since the reference system does not have any contribution from solar energy. The fuel savings were the highest in the PVT case, followed by PV with solar-assisted HP case and national grid and ST panels' case. The same authors used also other energy metrics, as will be discussed in the following.

3.1.2. Energy efficiency

Another energy type criterion that results from the 1st law of thermodynamics, is the energy efficiency. It represents the ratio between the amount of the produced energy over the amount of incident solar energy on the surface of the collector. The instantaneous electrical efficiency of PV panels is defined as the ratio of the electrical power produced to the

global incident solar irradiance on the surface of the panel, according to El-Bayeh et al. [18]. The instantaneous thermal efficiency of a ST collector can be defined similarly. However, in most studies averaged efficiencies are used. For a ST collector, it can be defined as the ratio of heat transferred to the heat transfer fluid by the panel over a given time period to the global incident solar radiation on the surface of the collector during the same period [19]. The period is often taken as a year, but can be defined as a day or a month as will be detailed in the following. The efficiency of the PVT panels is assessed on both the electrical and the thermal side. An overall efficiency mixing the electrical and thermal parts can thus be defined. Fig. 6 displays the values of energy efficiencies obtained throughout the different studies for the PVT panels.

In Eqs. (1) and (2), a general definition of the instantaneous and averaged efficiencies of a solar panel is presented.

$$\eta_{solar} = \eta_{electrical} + \eta_{thermal} = \frac{\dot{E}_{PV} + \dot{m}c_p(T_{out} - T_{in})}{A \cdot \dot{G}_{sol}} \quad (1)$$

$$\bar{\eta}_{solar} = \bar{\eta}_{electrical} + \bar{\eta}_{thermal} = \frac{E_{PV} + E_{thermal}}{A \cdot G_{sol}} \quad (2)$$

Daghigh et al. [20] presented a new water-based BIPVT collector design, considering factors such as thermal conductivity, fin efficiency, cell type, coolant, and operating conditions. Simulation results based on Malaysian meteorological conditions for a typical March day indicate that, as a function of the heat transfer fluid flow rate and specific solar radiation and ambient temperature, the amorphous silicon PVT module achieved an overall efficiency of 71 to 76 % while the crystalline silicon PVT module exhibited a overall efficiency between 56 and 62.5 %.

Abbas et al. [21] studied numerically and validated experimentally a series of hybrid PVT (1.25 m²) and flat plate ST collectors (2.25 m²), and summed the electrical (14.08 %) and thermal (60.12 %) efficiencies of the overall system to obtain the overall efficiency that achieved 74,2% daily. However (Table 3) this value is over-estimated compared to other studies as the incident flux \dot{G}_{sol} is decreased of the radiative losses of the upper-part of the collector in the efficiency evaluation (Eq. (1)).

A second energy type criterion used by Gagliano et al. [16] to compare different solar technologies is the energy efficiency. They used the typical definition as the sum of the electrical and thermal efficiency, but for ST panels \dot{G}_{sol} (Eq. (1)) is the incident solar irradiance, while for PVT panels, it is reduced by the amount of solar energy converted in the PV module into electrical energy. Consequently, the overall efficiency is

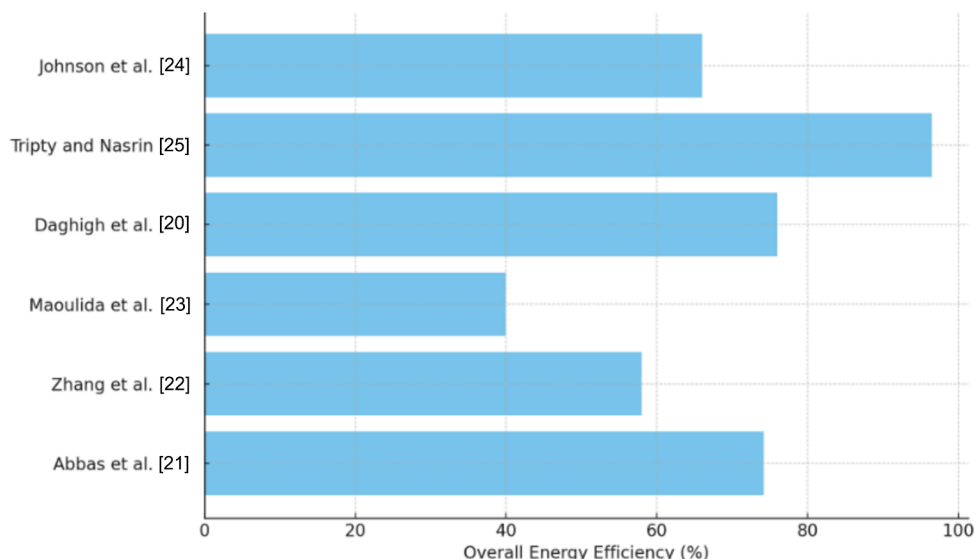


Fig. 6. Energy efficiencies of the PVT systems in the different studies.

here over-estimated compared to authors that use the same global incident solar flux. For the 3 locations considered, the overall efficiencies of the PVT panels are in average about 1 % greater than the PV panel efficiency.

Zhang et al. [22] presented a novel method of optimising the efficiency of PVT by spectral splitting with nanofluid, and explored the effect of varying the mass flow rate, as well as the influence of external operating conditions (solar radiation, external temperature, wind speed and optical thickness) on the overall system's efficiency. Their purpose was also to achieve an outlet temperature of 45 °C for building heating, and proposed a flexible control strategy to enhance the overall efficiency. During the entire heating season, their approach could achieve daily overall efficiency of 51.72 % in Zhengzhou, 57.63 % in Beijing, and 47.09 % in Harbin (China), with a collector area of 0.61 m².

Maoulida et al. [23] showcased the viability of PVT technology in the Comoros, by evaluating its performance in the local tropical climate and compared it to Mediterranean (Marseille) and continental (Longwy) climates. The study registered a maximum of 40 % average overall efficiency during one summer for the PVT panel in France, while the overall performance of the PVT panels was 40 % during the whole year in the Comoros.

In Johnson et al. [24], an Open Loop Photovoltaic Evacuated Tube Collector (OPVETC) panel was studied, which comprises a sheet-and-tube PVT collector array combined with an evacuated tube ST collector. The study parameters included the flow control strategy, the building's associated load demand and the interaction with the energy management system (EMS). This novel OPVETC was compared to a standard PVT system, and recorded an annual overall energy efficiency equal to 66 % compared to 53 % for the standard one in an optimal functioning configuration.

Recently, Tripty and Nasrin [25] studied numerically the influence of mass flow rate and inflow temperature on a PVT system overall efficiency. Overall efficiency increased with the mass flow rate increase and the decrease of the temperature of the inlet flow, as expected. It achieved overall efficiency between 61.5 % and 96.5 % but this value is over-estimated as in the case of Abbas et al. [21] (Table 3).

3.1.3. Solar fraction

In addition, an energy criterion allowing to measure the contribution of solar energy among the different building consumptions and thus to compare the integration of different solar technologies in the buildings, is also defined.

Kashan et al. [26] defined a solar fraction (SF) that shows the part of the DHW heating consumption that was covered by the useful solar energy. The solar systems compared were a novel micro-channel PVT (MCPVT) collector that consists of a micro-channel heat exchanger, a micro-channel solar thermal (MCST) system, and conventional PV and ST. All the solar systems were coupled with a HP. The SF was evaluated for five Canadian climates, different flow rates and tilt angles. The MCPVT-HP system exhibited the highest SF at 76.3 %, out passing a conventional flat-plate solar thermal collector by 6.1 % and a PV system by 58.3 %, while the MCST-HP system, with a 5.4 % higher SF than the flat-plate collector, showed only a 1.5 % difference from the MCPVT-HP.

Johnson et al. [24] also used the solar fraction, to compare their novel OPVETC (described in section 3.1.2) to a standard PVT system, and recorded an annual overall solar fraction equal to 87 % compared to 80 % for the standard one, in a health clinic integration.

3.1.4. Renewable energy fraction

Rosato et al. [27] described a second metric considering the integration in the building as the renewable energy fraction. It is the ratio between the overall energy (thermal and electric) demand covered thanks to the solar source and/or wood pellets in a series of 6 buildings and the overall energy (thermal and electric) needs of both the solar plant itself and the buildings. The needs consist of the total thermal energy demand for space heating and DHW production and the overall

electric energy requirements of both plant and district. The ratio achieved a renewable energy fraction of 66.1 %, which means that 66.1 % of the overall energy demand was covered by the renewable sources composed of PV panels and a wood pellet boiler. This renewable energy fraction is thus a broader view of the previous solar fraction.

In another paper, Rosato et al. [28] also evaluated the impact of the solar technology using the same metric, reaching overall renewable energy fraction as high as 96.8 %. This time, the renewable energy fraction is higher because the system was composed of a combination of PV and ST panels with electrical and thermal storage, and coupled to a wood pellet boiler.

3.1.5. Load cover factor and solar self-consumption

Kim et al. [29] defined indicators for the evaluation of the self-sufficiency of the three solar technologies in a grid integration context for residential houses in the Busan Eco Delta City, Korea. An initial BIPV installation was supplemented by other solar panel configurations, consisting of either PV, ST or PVT, and was coupled with HP (ground source or water), and a thermal energy storage (TES) at the village scale. Therefore, the solar panels either produced thermal energy that was directly stored in the TES, or electricity that was used by the HP or sent to an external electricity grid. A load cover factor (LCF) was defined. The LCF looks similar to the SF defined earlier, but the solar production is in that case not divided by the total energy consumption of the system, but by the useful energy need of the user. LCF values should be higher than SF values, as production devices also cover the losses of the network between the production and the user (typically losses in energy transfer or in energy storage). In Kim et al. [29] study, it represents the fraction of energy consumption met by the BIPV over the village energy load. For a same surface of additional installed PV, PVT and ST, the case with ST system exhibited higher LCF values than the BIPV and PVT systems. This is because ST system effectively meets a larger portion of the heating load directly with solar thermal energy, which reduces the reliance on grid electricity and thus increases the proportion of load covered by solar generation.

The evaluation of the case of Dimri and Ramousse [17] (presented in section 3.1.1) was also performed based on two other indicators for the energy part: the solar self-production and self-consumption mixing both forms of energy, thermal and electric. The self-production is actually a load cover factor. Here it is defined as the ratio of total useful energy produced by solar panels to the total demand of heating, DHW and specific electricity. The self-consumption is the ratio of total useful energy produced by solar panels to the total energy produced by solar panels. Here the authors separate the criteria as a function of the type of needs. The share of electrical energy produced by solar panels that is utilized to meet the electrical demand is calculated as the energy produced by the panels plus any supplementary energy from battery storage if the production is less than the demand, or equal to the demand if production exceeds it. The share of thermal energy produced by solar panels that is used for domestic hot water production is calculated based on the energy available in the DHW tank, which includes the thermal energy produced by the panels and any remaining energy from the previous hours, up to the current demand. The share of thermal energy produced by solar panels that is utilized for space heating, is calculated as the energy produced by the panels if it is less than or equal to the demand, or equal to the demand if production exceeds it, with any shortfall supplemented by an auxiliary system. Increasing the number of solar panels improves solar self-production but also rises the system cost, necessitating a balance between economic efficiency and environmental benefits. The case with PVT panels recorded the highest self-production rate, whereas the PV and ST used together met the highest self-consumption.

3.1.6. Net zero energy balance

Finally, Good et al. [30] compared different configurations composed of PV, ST and PVT systems in the aim to achieve a net zero

energy building. For that, they defined a criterion named net zero energy balance, calculated as the difference between the energy delivered/imported to the building and the energy exported from the building. They quantified it in six cases mixing the three solar technologies with a HP as auxiliary system. The system that was the closest to reaching the net zero energy balance was the case using only PV panels, reaching 73 %. In this study, the two types of energy (heat and electricity) were, however, not directly included in the criterion, as the only form of energy that was exchanged by the building was electricity (heat was produced on site by a HP). The solar heat was accounted as a decrease of the heat that needed to be produced by the HP, as the solar energy installations on the roof were considered to be inside the system boundary.

3.1.7. Discussion

Using energy to define criteria for comparing different technologies, such as their production, efficiency and solar fraction, is a very common and widely used practice within the studies analysed in this paper. The energy efficiency measures the conversion performance and operation of the solar systems. This performance indicator does not consider directly whether the energy produced by the collector matches the building demand. Using this evaluator gives an idea of how well the system converts the total incident energy to electrical or thermal energy without direct concern for its usefulness [24]. On the other hand, a crucial point for the ST collector yields and resulting system efficiency, is the match between the demand and the availability of the solar source [31]. In the case of ST panels, the efficiency criterion takes indirectly (through the temperature of the heat transfer fluid inside the collector) into account the usefulness of the heat.

Solar fraction, however, quantifies the solar contribution in a given environment. For one load, greater solar collectors' areas lead to higher annual solar fractions, but also to a lower specific solar production, decreasing the overall system efficiency. LCF and solar self-consumption

emphasize energy independence and focus on optimizing local energy use, each offering distinct insights with varying strengths and limitations.

For all the metrics that link the solar production to the needs, on-site energy storage is an important field to explore. The dimensioning of the storage system, or the lack of it in the case of direct transfer of PV electricity to the external grid, changes tremendously these metrics values. A comprehensive comparison among the three solar technologies is essential for understanding their relative performance. Ideally, such comparisons should be conducted within the same study, evaluating the technologies under identical climate and working conditions. Among the studies reviewed, eight specifically compared the three solar technologies, while others focused solely on PVT systems. The findings from these studies reveal several significant conclusions. Consistently, the electrical component of PVT systems is generally more efficient than that of standard PV systems. Additionally, PVT technologies often produce more energy than a combination of separate PV and ST systems for a same surface. ST systems demonstrate a higher rate of self-consumption due to their storage capabilities. Furthermore, the integration of auxiliary systems significantly enhances the self-consumption of electricity generated by both PV and PVT systems.

3.2. Primary energy criteria

Primary energy refers to energy in its raw form, extracted or harvested directly in natural resources form, such as fossil fuels (coal, oil, natural gas), nuclear fuels, and renewable sources (solar, wind, hydro) Frischknecht et al. [32]. These primary energy sources need to be converted into secondary forms of energy, better known as final energy, such as electricity or heat, to be used for various applications. The conversion process often involves the use of technologies like power plants or engines. This conversion efficiency assumes different values in

Table 4
Definition of the primary energy type criteria identified in the publications.

Criteria	Reference	Parametric study	Definition
Primary energy production	Huide et al. [63]	Location	Total useful equivalent thermal energy produced by PV and PVT converted using electricity-to-heat primary energy coefficient of 38 % (China).
Primary energy saving (PES)	Buonomano et al. [33]	Building/Location	Amount of energy saved between the reference case with heat pump/chiller and gas boiler for DHW, and cases with PVT and BIPVT, converting electricity into heat using efficiency of a conventional electric power production equal to 46 %.
	Dupeyrat et al. [34]	Location	PES of a solar DHW system evaluates the difference between the primary energy consumption of the auxiliary heating system (including solar pump) operating with or without solar panels
	Aste et al. [8]	Sizing/Location	The share of DHW demand that is covered by the solar system, converting the electricity used from the PVT to primary energy considering an electricity to primary energy conversion factor for Italian context equal to 46 %.
Primary energy efficiency	Gagliano et al. [16]	Location/Sizing	Here called 'primary efficiency', PV and PVT overall efficiency adding thermal production and electricity production converted to heat with grid efficiency coefficients of Split, Catania and Freiburg (36, 46 and 38.5 %), divided by the incident solar flux
	Barbu et al. [35]	Location	Electrical and thermal energies with electricity converted to heat with grid efficiency coefficient of two different locations in France and Romania equal to 60 and 53.2 %, with reference to a reference case.
Ratio of primary energy reduction	Ma et al. [36]	Location/Sizing	Overall energy efficiency of PVT with electricity generation converted using grid efficiency equal to 38 %
	Gagliano et al. [16]	Location/Sizing	Ratio between the PES in the configuration using solar panels and the primary energy consumption of the generic use (eg. Residential) using the electrical loads converted to heat with grid efficiency and thermal DHW energy demand with boiler efficiency.
	Ren et al. [37]	Building	The primary energy saving rate (PESR) of the hybrid CCHP system compared with the separated production system (electricity from grid and heating/cooling from GSHP).
	Martorana et al. [38]	Sizing	Non-renewable energy saving factor in comparison to a 100 % electrical storage water heater reference system, which is defined as the ratio of the useful energy output (DHW production by the ST) to the non-renewable primary energy input (electricity imported from the grid converted to its primary energy form using the Italian primary energy conversion factors equal to 51 %).
	Rosatoet al. [39]	Solar technology/Sizing	Here called Primary energy saving (PES) but defined as a ratio. The ratio of the primary energy saved by the proposed system that is a centralized solar heating plant with seasonal storage (CSHPSS) to that of the conventional system that is individual natural gas-fired boilers installed inside the buildings, considering energy consumed by components such as the main boiler, individual boilers, pumps, fan coils, auxiliaries, lighting, and domestic appliances.
Renewable primary energy fraction	Rosatoet al. [27]	Sizing	same as above.
	Rosatoet al. [28]	Solar technology	same as above.
	Rosatoet al. [28]	Sizing	The renewable energy fraction for the CSHPSS is determined by calculating the proportion of energy (both thermal and electric) supplied by solar sources and/or wood pellets compared to the total energy requirements of the plant and district.

each country as a function of its energetic mix. This section targets the 12 studies that used this metric to convert a form of energy (either electricity or heat) in their primary energy form. In Table 4 are summarised all the criteria belonging to the primary energy category, encountered in the studies, with their definitions and the parametric studies in which they have been used.

3.2.1. Primary energy production

Huide et al. [63] evaluated the performance of the three solar technologies, PV, ST and PVT, by comparing the total useful equivalent thermal energy produced by the three solar panels in four different locations in China. For that, the electricity produced by the PV and the PVT panels was converted into the heat form using a primary energy factor of produced electricity equal to 38 % for China. The assessment was done for an urban residential case where the available area for installing the solar collectors was assumed to be 3 m², and a rural case where the available area was wider and equal to 20 m². For Hong Kong, Lhasa, Shanghai, and Beijing, a solar system combining PVT and PV technologies achieved the highest total useful equivalent thermal energy and net annual electricity output, making it potentially the optimal choice among the other alternative solar systems considered.

3.2.2. Primary energy saving (PES)

Buonomano et al. [33] compared PVT panels in three different configurations used in a building context to a reference case of a heat pump/chiller and gas boiler for space heating/cooling, and DHW needs. The cases were as follows: a stand-alone PVT plant on the ground near the building, a roof integrated PVT, and the final case included a facade integrated PVT. Three thermal resistances of the building envelop, as well as four different climates of four European cities, ie. Freiburg (South-Germany), Milan (North-Italy), Naples (South-Italy) and Almeria (South-Spain), were parameters of the study. The primary energy saving (PES) was defined, as the amount of energy saved between the reference case without solar system, and cases with a solar system, converting electricity into heat using a heat-to-electricity coefficient. It was calculated dissociating the heating, cooling and DHW, and all electricity supplies were converted to heat using the efficiency for a conventional electricity production equal to 46 % for all the locations. The building integration helps to save heating and cooling loads of the building. Therefore, the useful passive effect of the BIPVT panels helped save more primary energy.

Dupeyrat et al. [34] operated an annual performance evaluation of DHW systems to compare conventional solar components (separate ST and PV panels) with a system incorporating both PVT and PV panels for a given surface. The comparison was made using the PES for three French cities. The analysis revealed higher thermal losses for the PVT collector, necessitating an increased PVT collector area to match the thermal output of a standard thermal collector installation. The remaining of the roof's surface was for the PV installation. Having PVT/PV installed together yields higher PES, compared to the combination of traditional ST collectors and PV panels. This holds true across all locations.

Finally, the primary energy saving was defined as an objective function to optimise the use of a PVT collector in Aste et al. [8] by evaluating the overall electrical and thermal production of the system when coupled to two different auxiliary systems. PVT systems offer greater primary energy savings with electric heaters compared to natural gas boilers, due to the respective conversion coefficients of 46 % for electric heaters and 100 % for gas boilers. However, increasing the PVT collector surface does not lead to proportional energy gains, as larger surfaces raise the heat transfer fluid temperature, diminishing both electrical and thermal efficiency.

3.2.3. Primary energy efficiency

Barbu et al. [35] evaluated the primary energy saving efficiency of a PVT collector used in a residential building for domestic hot water

(DHW) and electricity needs, for two different climate conditions in France and Romania. Compared to the first law efficiency that is a straightforward, commonly employed approach and that does not differentiate between electrical and thermal power, the primary energy efficiency considers regional variations in energy production, making it more valuable for comparing system efficiency in different locations, as exemplified in this study. They used a primary energy factor of produced electricity for both countries η_{Tpower} equal to 60 % for France and 53,2 % for Romania. However, these values are over-estimated, as they represent, in fact, the efficiency of electricity and heat production from conventional thermal plants (thus considering their cogeneration). The primary energy efficiency is defined following expression (3) considering both the thermal $\eta_{thermal}$ and the electrical one $\eta_{electrical}$ of the PVT panel converted to primary heat.

$$\eta_{primaryenergy} = \eta_{thermal} + \frac{\eta_{electrical}}{\eta_{Tpower}} \quad (3)$$

Ma et al. [36] evaluated PVT and ST performance combined together, in a residential building in China. They wanted to see the influence of solar radiation, mass flow rate and inlet water temperature on the PES efficiency. The conversion coefficient of electricity generation used was equal to 38 %. As a result, a total of 48 % of PES efficiency was achieved.

Gagliano et al. [16] compared PVT panels with the conventional PV and ST plants, in a residential tower building revealing the limited roof surface aspect, PVT being able to combine the production of both forms of energies in a same area, as discussed in section 3.1.1. They weighted the different configurations, also using the primary energy efficiency. PVT plants achieved energy efficiencies and primary energy efficiencies greater than the maximum efficiencies achievable by any configuration of the PV + ST plants. For the same PV + ST configuration, primary energy efficiencies are always greater than energy efficiencies as the first overestimated, through the η_{Tpower} coefficient, the electrical energy generated by the PV module.

3.2.4. Ratio of primary energy reduction

Along with energy and the previous metrics, Gagliano et al. [16] used also other indicators as ratio of primary energy reduction, and the study was conducted for three different European cities: Catania, Split and Freiburg as said before. The ratio of primary energy reduction is the share of the primary energy consumptions of the user (e.g. residential) provided by the solar system. The PVT plant allowed achieving 95 % of ratio of PES in Italy and Croatia while the PV and ST plant (90 % PV and 10 % ST) helped save 83 % in average for the three locations.

Ren et al. [37] and their multi-objective optimisation of combined cooling, heating and power (CCHP) generation systems utilizing PV, ST and PVT among other energy sources, used as one of their objective function the primary energy saving rate (PESR). It is defined using the annual benefits in the form of non-consumption of fossil fuel energy of the hybrid CCHP system versus another system using electricity from the grid and heat from a ground source heat pump. The electricity from the grid was converted in its primary energy form using for the energy efficiency of the power plant and transmission from the grid. The PESR in PV and ST mode is better than in PVT mode in this case.

Martorana et al. [38] assessed the performance of PV, ST and PVT coupled to HP for DHW generation, in terms of non-renewable primary energy ratio, in comparison to a reference system composed of an electric resistance water heater. They explored the influence of sizing by changing the number of panels on the ratio. The primary energy conversion factor of the electrical grid was equal to 51 % to convert electricity to heat form. In summary, plants with PV and PVT panels showed similar annual patterns, with the PER values increasing with panel size. Non-renewable PER correlated with solar energy availability for DHW production. ST plants, designed for substantial heat demand in this case study, had lower PER due to electrical consumption from solar pumps and increased grid reliance in winter due to the electric resistance water

heater back-up system.

Rosato et al. [39] also used the ratio of primary energy reduction with a national power plant average efficiency equal to 42 % in Italy. The purpose was to compare the use of a ST and PVT plant for heating and DHW consumption of a small district (6 residential buildings and 3 schools) in Napoli, to the use of a gas boiler and grid reference system. The parameters were the technology of the solar collectors and the control logic of the solar circuit (variable or constant flow). The values of ratio of primary energy reduction (between 4.6 and 11.3 %) were always positive proving that the new solar plant always helped reducing the primary energy consumption compared to the reference one.

In a second study, Rosato et al. [27] integrated a case with electric vehicles, borehole thermal energy storage for DHW, coupled with either ST or PV and ST and aimed to highlight the influence of the solar field area and the technologies for the back-up system. The case study with PV had the highest ratio of primary energy reduction. In a third study, Rosato et al. [28] again also evaluated the impact of the solar technology using the same metrics reaching ratio of primary energy reduction values as high as 94,9%, and the configuration of PV with a storage battery was the best-performing due to the higher electrical self-consumption of the PV.

3.2.5. Discussion

In most of the publications considering the primary energy criterion, the electrical energy was converted to heat by using a primary energy conversion coefficient. This coefficient is specific to each country in terms of the electrical mix, and considers the overall efficiency of the conversion through power generation, transmission, and distribution. The various values of the heat-to-electricity conversion coefficient encountered in the studies are summarized in Table 5.

Using the primary energy form requires the use of the heat-to-electricity conversion coefficient specific to each country or region, making the comparison of solar configurations in different locations difficult. Also, as stated in Table 5, the conversion coefficient changes for a same location depending on the year, see for example the case for Italy. Moreover, this criterion actually changes a lot depending on the moment of the year, so a more precise evaluation could be linked to the consideration of the variation of this criterion at short-term time steps. An important criterion is the PES, allowing a comparison of energy systems including different solar technologies to that of a reference system without solar panels. Primary energy evaluation is a common way to evaluate solar systems in the recent works (Fig. 3), and one of the different possibilities to consider the different forms of energy produced in the 3 types of solar collectors.

3.3. Exergy criteria

The concept that allows to combine different forms of energy is the First Law of Thermodynamics. However, the second law of thermodynamics can be considered as well. It introduces the concepts of entropy and exergy and the idea that not all energy transformations are reversible. In any energy conversion process, there are losses due to entropy generation, which might affect the usefulness of the different energy forms. So, while it's generally accepted to add different forms of energy together, it's crucial to do so while accounting for any energy conversion, efficiency losses, and irreversibilities that might be present in the system. The second law analysis, whether based on entropy or exergy, is crucial for optimizing processes and is applied to solar energy systems. No study based on the entropy generation was found in this review process. However, exergy analysis were numerous.

Exergy is a state function that refers to the reference conditions P_a and T_a , often stated as ambient conditions, which interact directly with the system, by modifying its performance. The reference conditions should be constant, as defended by the work of Pons [40]. However, in the context of solar exergy evaluation where the ambient conditions fluctuate due to the variation of the outdoor ambient air temperature,

Table 5

Electricity to heat primary energy conversion coefficients.

Place	Reference	Conversion coefficient
European	Buonomano et al. [33]	46 %
China	Huide et al [63] and Ma et al [36]	38 %
Italy	Rosato et al. [39]	42 %
Italy	Martorana et al. [38]	51 %
Italy	Aste et al. [8]	46 %
Catania, Sicily		46 %
Split, Croatia	Gagliano et al. [16]	36 %
Freiburg, Germany		38.5 %

researchers asked what temperature to take as a reference value. Kallio and Siroux [41] for example took the average monthly temperature. Pons [42] took instead the minimum temperature each day since the exergy was assessed on a daily basis.

In Table 6 are summarised all the criteria belonging to the exergy category, encountered in the studies, with their definitions and the parametric studies in which they have been used.

3.3.1. Exergy production

The definition of the useful exergy for solar panels is the useful energy part of both the electrical and thermal energy produced by the solar collectors. Yaghoubirad et al. [43] and Bayrak et al. [44] in their performance assessment of panels conducted the exergy analysis starting with the exergy balance equation as in Eq. (4). This balance equation is also valid for the other solar panels, ie. ST and PVT.

$$Ex_{in} = Ex_{out} + Ex_{loss} + Ir \quad (4)$$

The input exergy is, as will be discussed in section 3.3.2, the solar flux exergy: $Ex_{in} = Ex_{sun}$, whereas the output exergy Ex_{out} is the exergy produced by the solar panels, also called exergy yield. In the case of electricity generation, the electrical exergy Ex_{elec} is defined as the total electrical energy produced by the panel over a certain period (Eq. (5)), because electrical energy is seen as pure exergy [45]. For the heat produced by the panels, the expression of the thermal exergy $Ex_{thermal}$ follows Eq. (6) as stated in Kalogirou et al. [46] and Veyron et al. [47].

$$Ex_{electrical} = E_{pv} \quad (5)$$

$$Ex_{thermal} = \int_{t_{mi}}^{t_{final}} \dot{m}c_p \left[(T_{out} - T_{in}) - T_0 \ln \left(\frac{T_{out}}{T_{in}} \right) \right] dt \quad (6)$$

Dubey and Tiwari [48] quantified the overall exergy yield of six PVT flat plate collectors consisting on solar collectors of 2 m² covered partially in solar PV cells of 0.165 m², operating under different sets of weather data. The first one concerned four weather types of the city of New Delhi, consisting of different ratios of daily diffuse to daily global radiation and sunshine hours, and the second study tested five different cities in India. The total annual exergy yield is equal to 1273.7 kWh in New Delhi. Interestingly, the trends observed for the energy evaluation and exergy evaluation are similar.

In Dupeyrat et al. [34] (presented in section 3.2.2), exergy was also used to assess a PVT collector's electrical and thermal efficiency in comparison to a side-by-side PV and ST installation. The exergy output was slightly higher for all the three different locations for the PVT than for the conventional solar systems by 1,1%.

3.3.2. Exergy destruction

Buonomano et al. [49] conducted an exergy analysis of a BIPVT system across various European climate zones, along with an examination of the impact of the variation of the electricity storage capacity, on exergy destruction of both BIPVT collectors and electricity storage. Destroyed exergy is called Ir in Eq. (4). The BIPVT presents high destroyed exergy that is not considered as the most important parameter to consider, since BIPVT panels use the solar exergy input, which is a free

Table 6
Definition of the exergy type criteria identified in the publications.

Criterion	Reference	Parametric study	Definition
Exergy production	Dubey and Tiwari [48]	Sizing/ Location	Monthly electrical and thermal exergy production taking hourly ambient temperature as reference temperature (not constant).
	Dupeyrat et al. [34]	Location	Part of the energy that could theoretically be converted to work in an ideal Carnot process. No more details provided.
Exergy destruction	Buonomano et al. [49]	Sizing/ Location	Yearly destroyed exergy using the constant dead state ambient Temperature $T_a = 298$ K (value close to the annual average outdoor air temperature).
Exergy efficiency	Fuentes et al. [58]	Location	Exergy of ST heat and PV electricity production using the minimum outdoor temperature registered during the month over the exergy of solar radiation.
	Abbas et al. [21]	Location	Thermal and electric exergy over the exergy of solar radiation using steady state temperature reference. $T_0 = T_a$ (Eq. (6))
	Tian et al. [59]	Sizing	Thermal and electrical useful exergy over the exergy of solar radiation using non-constant ambient temperatures.
	Gürlichet al. [31]	Building/ Location	Electrical and thermal exergy efficiency over sun exergy, taking as reference temperature for the calculation of the exergy the average annual temperature of the 3 studied locations, at 286 K. For the exergy calculation of the heat of the ST and PVT, the temperature is assumed equal to 323 K, which is the temperature of the preheated DHW.
	Buonomano et al. [49]	Sizing/ Location	Thermal and electrical exergy over solar flux exergy, using the constant dead state temperature equal to 298 K

renewable and environmental-friendly source. In addition, the solar exergy input converted by solar collectors would be intrinsically destroyed when no BIPVT collector is considered. Therefore, the high destroyed exergies obtained for BIPVT absolutely do not suggest avoiding the use of such renewable energy technologies. The highest exergy destruction for BIPVT is observed in Larnaca compared to the lowest in Belfast, due to the incident solar radiation on BIPVT collectors of the selected weather zones: the higher the incident solar radiation, the greater the BIPVT exergy destruction.

3.3.3. Exergy efficiency

Solar systems differ from traditional systems in terms of the solar energy form they receive. To conduct a thorough second law analysis of a solar energy system, it is essential to evaluate the entropy and exergy flows associated with solar radiation on earth, considering its variability in intensity and quality, and its direct and diffuse components.

Pons [50] asked what the appropriate surface for integrating incident solar flux is. The collector surface isn't the most general concept as it involves specific choices about the collectors' type and positioning. Instead, the horizontal ground surface is more suitable for exergetic analysis, especially for decisions about the best type of solar installation on a given land surface. Pons assessed that the required sunlight data are the direct and diffuse radiation on the horizontal plane, measured with a small-time interval, and the incident exergy is calculated for this same plane. Expressions of the exergy with a distinction in the total, global, direct and diffuse flux/irradiation, were assessed and calculations were made on weather data from La Réunion. The exergetic content of solar irradiance received is variable throughout the day. The difference in exergy values indicates that flat collectors, ie. PV, ST and PVT, experience exergy loss because they do not exploit the directional nature of direct radiation. This systemic irreversibility contrasts with high-concentration collectors, which only use direct radiation and have minimal losses. In St-Pierre de la Réunion, the average daily global exergy is higher than the direct exergy (14.2 MJ.m^{-2} vs. 12.3 MJ.m^{-2}), suggesting flat collectors have more available exergy than high-concentration ones. In another work of Pons [51], where the weather data of Ouagadougou in Burkina-Faso was evaluated, the evaluation based on direct and diffuse radiation is more accurate than using the global radiation alone when daily incident energy is above 20 MJ.m^{-2} , with clear days showing greater exergy for direct + diffuse evaluations than global ones. However, often only measure of the global radiation is easily available, leading to a less precise exergy evaluation of the solar flux.

Moreover, discrepancies still appear in the recent evaluation of the solar exergy received between the 7 studies selected that conducted exergy analysis. As explained in Kalogirou et al. [52], what is used is an

expression of the exergy of the sun where the surface considered is A the solar panel's surface, and only the global component of the solar radiation G_{sol} is considered, and where the T_{sun} is the sun surface temperature taken as 5772 K, and T_0 is the reference temperature. Two approaches have been adopted for deriving the exergy of solar radiation. The first approach uses basic thermodynamic principles as in Eq. (7), while the second is based on empirical studies following Eq. (8). Table 7 displays the expressions of the solar exergy considered in each paper.

$$Ex_{sun} = AG_{sol} \left(1 - \frac{T_0}{T_{sun}} \right) \quad (7)$$

$$Ex_{sun} = AG_{sol} \left(1 - \frac{4}{3} \frac{T_0}{T_{sun}} + \frac{1}{3} \left(\frac{T_0}{T_{sun}} \right)^4 \right) \quad (8)$$

From the definitions of thermal and electrical exergy $Ex_{thermal}$ and Ex_{elec} , and the exergy balance in Eq. (4), exergy efficiency's definition follows as the ratio between the useful exergy produced by the panel Ex_{out} , and the exergy received on its surface from the sun Ex_{in} . The exergy efficiency of PV panels is defined as the ratio between the electrical power produced and the exergy of the global incident solar radiation on the surface of the panel [53]. The exergy efficiency of a ST collector is defined as the solar thermal exergy produced by the panel over the exergy of the global incident solar radiation on the surface of the collector [54], [47], [55]. The exergy efficiency of the PVT panels is assessed on both the electrical and the thermal side [55, [57]. In Eq. (9), a general definition of the exergy efficiency of a solar panel is presented.

$$\Phi_{solar} = \frac{Ex_{electrical} + Ex_{thermal}}{Ex_{sun}} \quad (9)$$

Regarding the 7 selected papers that processed exergy, Fuentes et al. [58] compared experimentally PV and PVT collectors, testing them during four days in a Spanish climate. They used the total exergy efficiency as a sum of the electrical energy of the PV in Eq. (5) and the thermal exergy following Eq. (6), and taking as a reference temperature the minimum outdoor temperature registered during the month the experimentation took place. The two systems showed very close overall exergy efficiencies, ranging between 16,1 % and 19,1 % for the PV panel, and slightly higher for the PVT, between 18,1 % and 19 %. The efficiencies are higher in winter than summer due to the high temperatures of the PV cells in August. Also, in August, the PVT efficiency showed a higher value than the PV, whereas in February the values were similar.

Tian et al. [59] presented a PVT panel cooled by nanofluid, and tested it for different contents of nanoparticles (between 0 and 1 %). Increasing the flow rate from 0.5 to 4 L per minute reduces the exergy efficiency by 2.03 %, while the inclusion of 1 % nanoparticles enhances

Table 7
Exergy calculation for the global solar radiation.

Reference	Expression for the solar radiation exergy
Dubey and Tiwari [48]	Eq. (8)
Dupeyrat et al. [34]	No equation mentioned
Buonomano et al. [49]	Eq. (7) in which the sun temperature is set at 4077 °C (3/4 of the corresponding black body temperature)
Fuentes et al. [58]	$Ex_{sun} = AG_{sol}$
Gürlich et al. [31]	Equation (8)
Tian et al. [59]	Equation (8)
Abbas et al. [21]	Equation (7)

exergy efficiency by 0.45 % at the lowest flow rate of 0.5 L per minute.

Gürlich et al. [31] compared the annual performance of a combined PVT collector system to separate ST and PV collectors, also exploring energy savings from building envelope improvements. Using simulations validated by experimental data, the study explores three residential buildings across different European climates, analysing their heat, cooling, and electricity needs alongside renewable energy supply. PVT collectors, serving both heat and electricity, offer higher exergetic efficiency compared to separate collectors by 6 to 7 %.

Buonomano et al. [49] conducted an exergy analysis of a BIPVT system as presented in section 3.3.2. BIPVT collector exergetic efficiencies ranged from 8.4 % in Larnaca to 8.8 % in Belfast, accordingly to the exergy destruction values presented before.

Abbas et al. [21] obtained an annual average exergy efficiency of 18,44 % for their solar system combining in series both PVT and ST collectors described in section 3.1.2, and considering that the collector is in a steady state for each time step. Here, contrarily to their energy analysis (Table 3), the global incident solar flux was used in their exergy efficiency calculation. Fig. 8 displays all the values for the exergy efficiencies of the different solar systems met in the 7 papers discussed above.

3.3.4. Discussion

Exergy is a valuable way to compare electricity and heat, still not many studies include it in their criteria' definitions. Among the reviewed studies, five specifically addressed exergy assessments of the three solar technologies, while others focused solely on PVT systems. The main conclusions drawn from these studies indicate that while exergy provides valuable insights for comparing electricity and heat, thermal exergy efficiency is lower than that of energy efficiency which makes the efficiencies of PV, ST, and PVT more comparable. In addition, the definition of the exergy received from the sun on the solar collectors is still a subject of disparities between the recent studies as seen in Table 7. Some authors set that the difference between the results coming from these 3 calculation methods are less than 2 % [60]. All the studies only take the global solar radiation without considering the direct and diffuse components of solar radiation. This can be done only when the total solar radiation does not exceed high values ($20 \text{ MJ}\cdot\text{m}^{-1}$ according to Pons [51]).

3.4. Energy equivalence criteria

Other papers used an energy equivalence process to convert one form of energy to another, with the use of other metrics than the primary energy factor. Two studies used electricity-to-heat coefficients. In Table 8 are summarized all the criteria belonging to the energy equivalence category encountered in the 2 studies, with their definitions and the parametric studies in which they have been used.

Delisle and Kummert [61] suggested a novel approach to evaluate the performance of a PVT collector that produces both electricity and heat, in comparison to a combination of PV and ST. They evaluated the net annual combined useful equivalent thermal energy production, by

converting the electricity production into thermal equivalent form. For that, three conversion coefficients were utilized depending on the specific house HVAC system and fuel employed. These conversion efficiency factors were equal to 1, 2 and 3. To keep the study as general as possible without modeling any building energy load, the calculation of the energy production of the PVT panel was conducted for 16 different cases of water temperature rise at the heat exchanger and maximum (35 °C) and minimum (−30 °C) ambient air temperatures. To highlight the effectiveness of this methodology, a case study for a residential building in Montreal was conducted. This study highlighted that the advantage of implementing a residential BIPVT system over a conventional system comprising PV modules and solar thermal collectors' side by side significantly depends on the conversion factor of the equivalent thermal energy. The BIPVT system consistently produces at least the same amount of useful equivalent thermal energy as the PV + T system when using a conversion efficiency factor of three. When the BIPVT system produces more useful thermal energy than the PV + ST system, its benefit in terms of equivalent thermal energy production is greater with a conversion efficiency factor of 1 than of 3, as the thermal energy value is not diminished compared to electrical energy. Conversely, when the BIPVT system produces less useful thermal energy than the PV + ST system, the benefit is greater with a conversion efficiency factor of 3 than with a conversion efficiency factor of 1.

Vassiliades et al. [62] aimed to compare the integration of BIPVT system in a building alongside a heat pump/chiller for the heating, cooling and electricity needs. The evaluation of the BIPVT panel was conducted in terms of the energy saving in comparison to a reference case with no BIPVT. For that, the electricity needed from the grid was calculated by summing the heating and cooling loads converted to electricity using the coefficient of performances (COP) of the corresponding heat pumps chillers, plus the electrical load due to appliances. The energy saving is then evaluated as the difference between these latter, and was assessed for two different cities in Italy and Cyprus and for two different scenarios for HVAC, where the devices were either turned on non-stop during the heating and cooling season, or scheduled. Scheduling the HVAC set point helped save more equivalent energy than the non-scheduled one.

3.5. Discussion

Energy equivalence using an efficiency of a given HVAC system is another way to compare electricity and heat. The specific applications for thermal and electrical energy and the reference equipment being replaced are crucial factors in assessing the feasibility and performance of adopting a solar system from an energy perspective.

4. Conclusion and perspective

With the three solar technologies supplying the two forms of energy, and the different needs they also have to meet in a building, it is important to be able to compare them on a common basis in terms of efficiency and response to the needs. This will help integrate them as efficiently as possible in the building, alongside other energy supply systems and storage. Countless studies studied the performance of solar panels in their different forms separately, and under different aspects. In this paper, a focus was placed on studies that defined energy performance criteria combining both forms of energies, electricity and heat, that were selected following a systematic review protocol. The main points appearing in these papers can be summarized as follows:

- When dealing with different forms of energy, the primary energy conversion factor is the most used. Usually, the electricity is converted into its primary energy form using a national primary energy factor. This factor changes from a location to another making the comparison of the different solar technologies dependent on the country of installation and its actual energy mix which can change

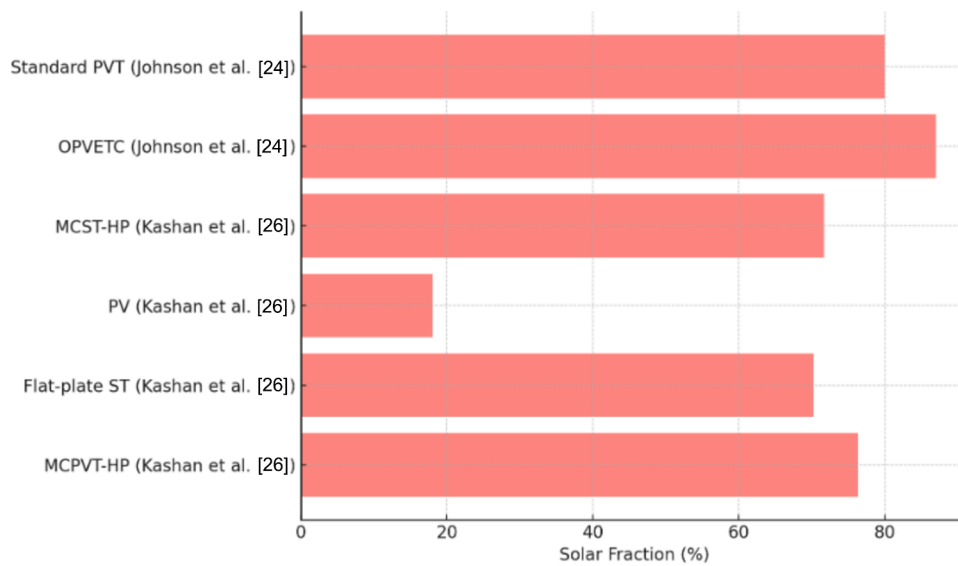


Fig. 7. Solar fractions in different solar systems.

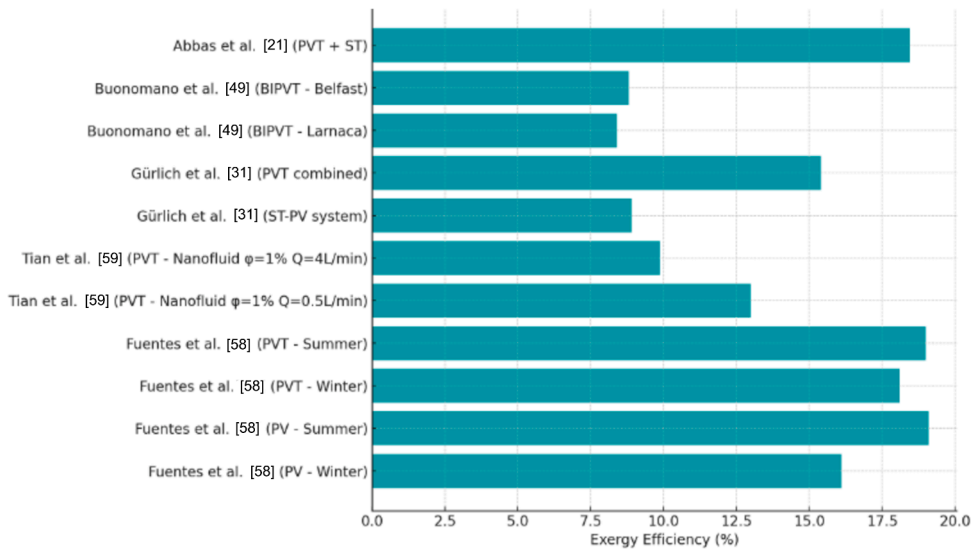


Fig. 8. Exergy efficiencies in different studies and systems.

Table 8

Definition of the energy equivalence type criteria identified in the publications.

Criteria	Reference	Parametric study	Definition
Energy production	Delisle and Kummert [61]	Sizing/The criterion	Net annual thermal and electrical useful equivalent thermal energy production, with electricity converted to heat using three conversion coefficients (equal to 1, 2 and 3).
Energy saving	Vassiliades et al. [62]	Sizing/Location	Considering all heating and cooling supplies are electrical because they are met by a heat pump/chiller (considering the COP of the HP), the primary energy saving is the difference between the electricity imported from the grid in the reference case without solar panels and the case with BIPVT and BIPV.

over time. As the energy mix evolves, with shifts in the proportions of renewable versus fossil fuel sources, it becomes increasingly important to consider these dynamic factors for accurate assessments of solar technology performance. Considering the variability of the energy mix can also guide the optimal use of solar panels—encouraging self-consumption during periods of high carbon intensity in the grid and drawing from the grid when it has a lower carbon footprint.

- The first law of thermodynamics allows mixing different forms of energies through energy efficiency definition for example, and it is a fairly common practice. However, it is also important to consider the different forms of energy. For that, second law is introduced and exergy is a key metric to account for the difference between the quality of energies. The studies agree on the definitions of the solar panels useful energy, but define different reference temperatures to account for the state function of exergy quantification. In addition, for the assessment of the solar radiation exergy, only the global

component is considered justified by the fact that non-concentrated solar panels do not differentiate between the direct and diffuse solar received radiation. Three different ways to quantify the solar flux exergy are still used in the recent works.

- Converting both the solar energy production and the building loads using efficiencies of energy systems such as heat pumps or boilers is also a solution utilized in a few studies. It offers a specific comparison that considers the actual energy performance of the HVAC energy system considered.
- The findings from the reviewed papers indicate that the solar fractions are particularly relevant for energy evaluations, as they account for both the efficiency of the solar panels and their ability to meet specific energy needs. When combined with considerations of self-consumption, these ratios provide valuable insights into the practical implementation of solar technologies. However, this raises questions about what these ratios would be if exergy or energy equivalence metrics were used instead. Exploring these alternative metrics could yield new perspectives on energy performance and inform future research directions in optimizing solar energy systems.
- This study significantly enhances the methodology for assessing exergy related to solar irradiance and solar panel performance. By establishing precise reference temperatures tailored to specific conditions and implementing daily assessments, researchers can achieve a more accurate quantification of exergy that reflects the true quality and utility of the energy produced, as well as insights into its availability and fluctuations throughout the day.

The study revealed four metrics categories used when trying to compare heat and electricity production simultaneously in the context of solar panels' performance evaluation and comparison. While some comparisons between metrics were discussed, none of the studies above compared the different metrics to each other to address a general conclusion on which to adopt. Further investigations are necessary, to reveal the relevance of each metric compared to another. In addition, other aspects such as economic, environmental, technical and social criteria are used to quantify the use of the different solar panels and should be considered.

CRediT authorship contribution statement

Hafsa Fares: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Nolwenn Le Pierrès:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **David Chèze:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Etienne Wurtz:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

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.

Acknowledgment

This work has benefited of a grant from French Alternative Energies and Atomic Energy Commission (CEA), Université Savoie Mont Blanc (USMB) and Conseil Savoie Mont-Blanc (CSMB).

References

- [1] IEA. Buildings - Energy System, 2023. <https://www.iea.org/energy-system/buildings>, visited 2023-08-22.
- [2] T. Abergel, J. Dulac, I. Hamilton, M. Jordan, and A. Pradeep. 2019 global status report for buildings and construction: Towards a zero-emission, efficient and

resilient buildings and construction sector. Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme, 2019.

- [3] E. Çam, Z. Hungerford, N. Schoch, F. Pinto Miranda, and C. D. Yáñez de León. Electricity 2024 - Analysis and forecast to 2026. International energy agency, 2024.
- [4] IEA. World Energy Outlook 2020. <https://www.iea.org/reports/world-energy-outlook-2020>, visited 2024-09-27.
- [5] H. Gholami, H.N. Rostvik, K. Steemers, The Contribution of Building-Integrated Photovoltaics (BIPV) to the Concept of Nearly Zero-Energy Cities in Europe: Potential and Challenges Ahead, *Energies* 14 (2021) 6015, <https://doi.org/10.3390/en14196015>.
- [6] M. Ahmadinejad, R. Moosavi, Energy and exergy evaluation of a baffled-nanofluid-based photovoltaic thermal system (PVT), *Int. J. Heat Mass Transf.* (2022), <https://doi.org/10.1016/j.ijheatmasstransfer.2022.123775>.
- [7] E. Assareh, S.S.M. Asl, N. Agarwal, M. Ahmadinejad, M. Ghodrati, New optimized configuration for a hybrid PVT solar/electrolyzer/absorption chiller system utilizing the response surface method as a machine learning technique and multi-objective optimization, *Energy* (2023), <https://doi.org/10.1016/j.energy.2023.128309>.
- [8] N. Aste, C. Del Pero, Optimization of Solar Thermal Fraction in PVT Systems, *Energy Procedia* 30 (2012) 8–18, <https://doi.org/10.1016/j.egypro.2012.11.003>.
- [9] W. Mengist, T. Soromessa, G. Legese, Method for conducting systematic literature review and meta-analysis for environmental science research, *MethodsX* 7 (January 2020) 100777, <https://doi.org/10.1016/j.mex.2019.100777>.
- [10] M. Herrando, C.N. Markides, Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations, *Appl. Energy* 161 (2016) 512–532, <https://doi.org/10.1016/j.apenergy.2015.09.025>.
- [11] M. Deymi-Dashtebayaz, A. Nikitin, V. Davoodi, V. Nikitina, M. Hekmatshoar, V. Shein, A new multigenerational solar energy system integrated with near-zero energy building including energy storage-A dynamic energy, exergy, and economic-environmental analyses, *Energy. Conver. Manage.* (2022), <https://doi.org/10.1016/j.enconman.2022.115653>.
- [12] N. Khordehgah, V. Guichet, S.P. Lester, H. Jouhara, Computational study and experimental validation of a solar photovoltaics and thermal technology, *Renew. Energy* (2019), <https://doi.org/10.1016/j.renene.2019.05.108>.
- [13] M. Souliotis, G. Panaras, P.A. Fokaides, S. Papaefthimiou, S.A. Kalogirou, Solar water heating for social housing: Energy analysis and Life Cycle Assessment, *Energy Buildings* (2018), <https://doi.org/10.1016/j.enbuild.2018.03.048>.
- [14] K. Wang, M. Herrando, A.M. Pantaleo, C.N. Markides, Technoeconomic assessments of hybrid photovoltaic-thermal vs. conventional solar-energy systems: Case studies in heat and power provision to sports centres, *Appl. Energy* (2019), <https://doi.org/10.1016/j.apenergy.2019.113657>.
- [15] S. Baur, J. Lamson, Thermal energy performance of a solar thermal electric panel, *J. Energy Eng.* (2012), [https://doi.org/10.1061/\(ASCE\)EY.1943-7897.0000065](https://doi.org/10.1061/(ASCE)EY.1943-7897.0000065).
- [16] A. Gagliano, G.M. Tina, S. Aneli, S. Nizetic, Comparative assessments of the performances of PV/T and conventional solar plants, *J. Clean. Prod.* 219 (May 2019) 304–315, <https://doi.org/10.1016/j.jclepro.2019.02.038>.
- [17] N. Dimri, J. Ramousse, Thermoeconomic optimization and performance analysis of solar combined heating and power systems: A comparative study, *Energy. Conver. Manage.* 244 (2021) 114478, <https://doi.org/10.1016/j.enconman.2021.114478>.
- [18] C.Z. El-Bayeh, K. Alzaareer, B. Brahmi, M. Zellagui, U. Eicker, An original multi-criteria decision-making algorithm for solar panels selection in buildings, *Energy* 217 (February 2021) 119396, <https://doi.org/10.1016/j.energy.2020.119396>.
- [19] S. Launay, B. Kadoch, O. Le Métayer, C. Parrado, Analysis strategy for multi-criteria optimization: Application to inter-seasonal solar heat storage for residential building needs, *Energy* 171 (March 2019) 419–434, <https://doi.org/10.1016/j.energy.2018.12.181>.
- [20] R. Daghigh, A. Ibrahim, G.L. Jin, M.H. Ruslan, K. Sopian, Predicting the performance of amorphous and crystalline silicon based photovoltaic solar thermal collectors, *Energy. Conver. Manage.* 52 (3) (2011) 1741–1747, <https://doi.org/10.1016/j.enconman.2010.10.039>.
- [21] S. Abbas, J. Zhou, A. Hassan, Y. Yuan, S. Yousuf, Y. Sun, C. Zeng, Economic evaluation and annual performance analysis of a novel series-coupled PV/T and solar TC with solar direct expansion heat pump system: An experimental and numerical study, *Renew. Energy* 204 (2023) 400–420, <https://doi.org/10.1016/j.renene.2023.01.032>.
- [22] C. Zhang, C. Shen, Y. Zhang, J. Pu, Feasibility investigation of spectral splitting photovoltaic/thermal systems for domestic space heating, *Renew. Energy* 192 (2022) 231–242, <https://doi.org/10.1016/j.renene.2022.04.126>.
- [23] F. Maouilda, R. Djedjig, M. A. Kassim, and M. El Ganaoui. Numerical Study for the Evaluation of the Effectiveness and Benefits of Using Photovoltaic-Thermal (PV/T) System for Hot Water and Electricity Production under a Tropical African Climate: Case of Comoros. *Energies*, 16(1), January 2023. doi:doi.org/10.3390/en16010240.
- [24] Z.S. Johnson, Y.A. Abakar, N.N. Caleb, B. Chen, An open-loop hybrid photovoltaic solar thermal evacuated tube energy system: A new configuration to enhance techno economic of conventional photovoltaic solar thermal system, *Journal of Building Engineering* 82 (April 2024) 108000, <https://doi.org/10.1016/j.jobe.2023.108000>.
- [25] T.A. Tripty, R. Nasrin, Efficiency upgrading of solar PVT finned hybrid system in Bangladesh: Flow rate and temperature influences, *Heliyon* 10 (7) (April 2024) e28323, <https://doi.org/10.1016/j.heliyon.2024.e28323>.
- [26] M.E. Kashan, A.S. Fung, J. Swift, Integrating novel microchannel-based solar collectors with a water-to-water heat pump for cold-climate domestic hot water

- supply, including related solar systems comparisons, *Energies* 14 (2021) 4057, <https://doi.org/10.3390/en14134057>.
- [27] A. Rosato, A. Ciervo, G. Ciampi, M. Scorpio, F. Guarino, S. Sibilio, Impact of solar field design and back-up technology on dynamic performance of a solar hybrid heating network integrated with a seasonal borehole thermal energy storage serving a small-scale residential district including plug-in electric vehicles, *Renew. Energy* 154 (2020) 684–703, <https://doi.org/10.1016/j.renene.2020.03.053>.
- [28] A. Rosato, A. Ciervo, G. Ciampi, M. Scorpio, F. Guarino, S. Sibilio, Energy, environmental and economic dynamic assessment of a solar hybrid heating network operating with a seasonal thermal energy storage serving an Italian small-scale residential district: Influence of solar and back-up technologies, *Therm. Sci. Eng. Prog.* 19 (2020) 100591, <https://doi.org/10.1016/j.tsep.2020.100591>.
- [29] M.-H. Kim, Y. An, H.-J. Joo, D.-W. Lee, and J.-H. Yun. Self-Sufficiency and Energy Savings of Renewable Thermal Energy Systems for an Energy-Sharing Community. *Energies*, 14(14), July 2021. doi:10.3390/en14144284.
- [30] C. Good, I. Andresen, A.G. Hestnes, Solar energy for net zero energy buildings – A comparison between solar thermal, PV and photovoltaic–thermal (PV/T) systems, *Sol. Energy* 122 (December 2015) 986–996, <https://doi.org/10.1016/j.solener.2015.10.013>.
- [31] D. Gürlich, A. Dalibard, U. Eicker, Photovoltaic-thermal hybrid collector performance for direct trigeneration in a European building retrofit case study, *Energy Buildings* 152 (2017) 701–717, <https://doi.org/10.1016/j.enbuild.2017.07.081>.
- [32] R. Frischknecht, F. Wyss, S. Büsser Knöpfel, T. Lützkendorf, and M. Balouktsi. Cumulative energy demand in LCA: the energy harvested approach. *The International Journal of Life Cycle Assessment*, 20 (7):957–969, July 2015. doi: 10.1007/s11367-015-0897-4.
- [33] A. Buonomano, F. Calise, A. Palombo, M. Vicidomini, BIPVT systems for residential applications: An energy and economic analysis for European climates, *Appl. Energy* 184 (December 2016) 1411–1431, <https://doi.org/10.1016/j.apenergy.2016.02.145>.
- [34] P. Dupeyrat, C. Menezo, and S. Fortuin. Study of the thermal and electrical performances of PVT solar hot water system. *Energy and Buildings*, 68(PART C): 751 – 755, 2014. doi:10.1016/j.enbuild.2012.09.032.
- [35] M. Barbu, G. Darie, and M. Siroux. Analysis of a residential photovoltaic-thermal (PVT) system in two similar climate conditions. *Energies*, 12(19), 2019. doi: 10.3390/en12193595.
- [36] T. Ma, M. Li, A. Kazemian, Photovoltaic thermal module and solar thermal collector connected in series to produce electricity and high-grade heat simultaneously, *Appl. Energy* 261 (2020) 114380, <https://doi.org/10.1016/j.apenergy.2019.114380>.
- [37] F. Ren, Z. Wei, X. Zhai, Multi-objective optimization and evaluation of hybrid CCHP systems for different building types, *Energy* 215 (January 2021) 119096, <https://doi.org/10.1016/j.energy.2020.119096>.
- [38] F. Martorana, M. Bonomolo, G. Leone, F. Monteleone, G. Zizzo, M. Beccali, Solar-assisted heat pumps systems for domestic hot water production in small energy communities, *Sol. Energy* 217 (2021) 113–133, <https://doi.org/10.1016/j.solener.2021.01.020>.
- [39] A. Rosato, A. Ciervo, G. Ciampi, S. Sibilio, Effects of solar field design on the energy, environmental and economic performance of a solar district heating network serving Italian residential and school buildings, *Renew. Energy* 143 (2019) 596–610, <https://doi.org/10.1016/j.renene.2019.04.151>.
- [40] M. Pons, On the reference state for exergy when ambient temperature fluctuates, *Int. J. Thermodyn.* 12 (3) (2009) 113–121.
- [41] S. Kallio, M. Siroux, Energy Analysis and Exergy Optimization of Photovoltaic-Thermal Collector, *Energies* 13 (19) (October 2020) 5106, <https://doi.org/10.3390/en13195106>.
- [42] M. Pons, Exergy Analysis and Process Optimization with Variable Environment Temperature, *Energies* 12 (24) (December 2019) 4655, <https://doi.org/10.3390/en12244655>.
- [43] M. Yaghoubirad, N. Azizi, A. Ahmadi, Z. Zarei, S.F. Moosavian, Performance assessment of a solar PV module for different climate classifications based on energy, exergy, economic and environmental parameters, *Energy Rep.* 8 (October 2022) 68–84, <https://doi.org/10.1016/j.egyr.2022.05.100>.
- [44] F. Bayrak, N. Abu-Hamdeh, K.A. Alnefaie, H.F. Öztö, A review on exergy analysis of solar electricity production, *Renew. Sustain. Energy Rev.* 74 (July 2017) 755–770, <https://doi.org/10.1016/j.rser.2017.03.012>.
- [45] S. Kallio, M. Siroux, Exergy and Exergy-Economic Approach to Evaluate Hybrid Renewable Energy Systems in Buildings, *Energies* 16 (3) (January 2023) 1029, <https://doi.org/10.3390/en16031029>.
- [46] S.A. Kalogirou, S. Karellas, V. Badescu, K. Braimakis, Exergy analysis on solar thermal systems: A better understanding of their sustainability, *Renew. Energy* 85 (January 2016) 1328–1333, <https://doi.org/10.1016/j.renene.2015.05.037>.
- [47] M. Veyron, D. Mugnier, F. Renaude, and M. Clausse. Dynamic exergoeconomic analysis of a solar district heating system located in the North West of France. In ECOS 2021, 34th International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems, Giardini Naxos, Italy, June 2021.
- [48] S. Dubey, G.N. Tiwari, Analysis of PV/T flat plate water collectors connected in series, *Sol. Energy* 83 (9) (2009) 1485–1498, <https://doi.org/10.1016/j.solener.2009.04.002>.
- [49] A. Buonomano, F. Calise, A. Palombo, and M. Vicidomini. Transient analysis, exergy and thermo-economic modelling of facade integrated photovoltaic/thermal solar collectors. *Renewable Energy*, 137(SI):109–126, July 2019. doi:10.1016/j.renene.2017.11.060.
- [50] M. Pons, Méthode pour analyses exergétiques robustes d’installations solaires et de bâtiments, *Actes Int. Building Performance Simulation Association (IBPSA-France) Conference* (2008).
- [51] M. Pons. Exergie en environnement réel pour la climatisation solaire. ORASOL project, ANR-PREBAT, LPBS St-Pierre de la Réunion, 2008a.
- [52] S.A. Kalogirou, S. Karellas, K. Braimakis, C. Stanciu, V. Badescu, Exergy analysis of solar thermal collectors and processes, *Prog. Energy Combust. Sci.* 56 (September 2016) 106–137, <https://doi.org/10.1016/j.pecs.2016.05.002>.
- [53] S. Kavian, C. Aghanajafi, H.J. Mosleh, A. Nazari, A. Nazari, Exergy, economic and environmental evaluation of an optimized hybrid photovoltaic-geothermal heat pump system, *Appl. Energy* 276 (October 2020) 115469, <https://doi.org/10.1016/j.apenergy.2020.115469>.
- [54] M. Murugan, A. Saravanan, P.V. Elumalai, P. Kumar, C.A. Saleel, O.D. Samuel, M. Setiyo, C.C. Enweremadu, A. Afzal, An overview on energy and exergy analysis of solar thermal collectors with passive performance enhancers, *Alex. Eng. J.* 61 (10) (October 2022) 8123–8147, <https://doi.org/10.1016/j.aej.2022.01.052>.
- [55] D. Nikolic, J. Skerlic, J.J. Radulovic, A. Miskovic, R. Tamasauskas, J. Sadauskiene, Exergy efficiency optimization of photovoltaic and solar collectors’ area in buildings with different heating systems, *Renew. Energy* 189 (1063–1073) (April 2022).
- [56] A. Farzanehnia, M. Sardarabadi, A. Farzanehnia. Exergy in Photovoltaic/Thermal Nanofluid-Based Collector Systems. *IntechOpen*, October 2019. ISBN 978-1-78984-675-1. doi:10.5772/intechopen.85431.
- [57] A.S. Joshi, I. Dincer, B.V. Reddy, Performance analysis of photovoltaic systems: A review, *Renew. Sustain. Energy Rev.* 13 (8) (October 2009) 1884–1897, <https://doi.org/10.1016/j.rser.2009.01.009>.
- [58] M. Fuentes, M. Vivar, J. de la Casa, J. Aguilera, An experimental comparison between commercial hybrid PV-T and simple PV systems intended for BIPV, *Renew. Sustain. Energy Rev.* 93 (October 2018) 110–120, <https://doi.org/10.1016/j.rser.2018.05.021>.
- [59] M.-W. Tian, Y. Khetib, S.-R. Yan, M. Rawa, M. Sharifpur, G. Cheraghian, A. A. Melaibari, Energy, exergy and economics study of a solar/thermal panel cooled by nanofluid, *Case Stud. Therm. Eng.* 28 (December 2021) 101481, <https://doi.org/10.1016/j.csite.2021.101481>.
- [60] T.T. Chow, G. Pei, K.F. Fong, Z. Lin, A.L.S. Chan, J. Ji, Energy and exergy analysis of photovoltaic-thermal collector with and without glass cover, *Appl. Energy* 86 (2009) 310–316, <https://doi.org/10.1016/j.apenergy.2008.04.016>.
- [61] V. Delisle, M. Kummert, A novel approach to compare building-integrated photovoltaics/thermal air collectors to side-by-side PV modules and solar thermal collectors, *Sol. Energy* 100 (February 2014) 50–65, <https://doi.org/10.1016/j.solener.2013.09.040>.
- [62] C. Vassiliades, G. Barone, A. Buonomano, C. Forzano, G.F. Giuzio, A. Palombo, Assessment of an innovative plug and play PV/T system integrated in a prefabricated house unit: Active and passive behaviour and life cycle cost analysis, *Renew. Energy* 186 (March 2022) 845–863, <https://doi.org/10.1016/j.renene.2021.12.140>.
- [63] F. Huide, Z. Xuxin, M. Lei, Z. Tao, W. Qixing, S. Hongyuan, A comparative study on three types of solar utilization technologies for buildings: Photovoltaic, solar thermal and hybrid photovoltaic/thermal systems, *Energ. Convers. Manage.* 140 (May 2017) 1–13, <https://doi.org/10.1016/j.enconman.2017.02.059>.