Energy Performance and Environmental Impact of Solar Photovoltaic, Thermal and Hybrid PVT Panels in an Individual House

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Abstract

The solar energy market has experienced significant fluctuations due to technological advancements, economic considerations, and regulatory dynamics. Despite widespread efforts, integrating solar technologies into buildings still faces some challenges. An important question in this context is the choice between electrical and thermal recovery systems, which depends on specific building requirements where there is a clear demand for both types of energy. Therefore, the objective of this work is to assess the performance of diverse building integrated solar solutions, i.e. photovoltaic, solar thermal and hybrid photovoltaic and thermal collectors, by defining key performance indicators that encompass both electricity and heat aspects, considering both energy efficiency and environmental impact, and using metrics that follow first and second law of thermodynamics, primary energy and energy equivalence. From an energy performance perspective, exergy and energy equivalence, which evaluates the systems based on their ability to produce useful work or heat-equivalent energy, allows a fairer comparison. From the environmental impact assessment point of view, the study concludes that while solar thermal is the most efficient and environmentally friendly option overall and photovoltaic excels in material efficiency for heat-equivalent energy, the analysis of photovoltaic and thermal is limited as it is based on only one industrial reference, unlike the average panels used for the two other panels.

Keywords: Photovoltaic, solar thermal, hybrid PVT, energy performance, Life cycle assessment, primary energy, exergy, coefficient of performance, building.

1. Introduction

1.1. Solar photovoltaic, thermal and hybrid PVT in building application :

With the word facing a severe climate change crisis and the important demand for energy in the building sector, which amounts to more than 30% worldwide and causes more than 26% of global greenhouse gas emissions, implementing renewable energy sources within the building represents one of the key actions to reduce their environmental impact and greenhouse gas emissions. Among the renewable energy sources, solar energy stands out as a promising candidate offering abundant and clean energy potential.

Active solar panels, which include photovoltaic (PV), solar thermal (ST), and hybrid photovoltaic and thermal (PVT) systems, offer a versatile solution to meet building energy needs. These three solar technologies are primarily used for building applications, unlike concentrated solar power (CSP) technology, which is typically associated with large-scale power generation in solar thermal power plants rather than residential or commercial buildings. PV panels convert sunlight into electricity, addressing the global demand for power that is projected to rise by 30% by 2030. ST systems capture solar heat for building heating and hot water production, crucial aspect given that heating accounts for about 47% of energy use in residential buildings. Hybrid PVT systems combine the benefits of both PV and ST, providing both thermal and electrical energy, and represent a comprehensive approach to achieving energy independence and reducing reliance on traditional power sources. Furthermore, in its renewable energy report in Abdelilah et al. (2023), the International Energy Agency (IEA) predicts that global heat consumption in the building sector will remain stable from 2023 to 2028. However, modern renewable energy sources for space and water heating are expected to grow by nearly 40%, increasing their share of the building sector's heat consumption from 15% in 2023 to 21% in 2028. The IEA highlights that renewable electricity will be the fastest-growing renewable heat source in buildings, expanding by two-thirds globally and accounting for almost 40% of the increase in renewable heat consumption.

On the one hand, the presence of heat and electricity in building use complicates the adoption of solar technologies. Buildings do not only require electricity for lighting and appliances but also rely heavily on heat for space and water heating. On the other hand, the diversity of solar technologies available, from PV systems to solar thermal collectors ST and hybrid solutions PVT, producing either electricity and/or heat, adds a layer of complexity.

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Understanding how these technologies perform in terms of energy generation and environmental impact is crucial for making informed decisions regarding their implementation.

1.2. Insights from previous research : KPI used to compare different solar panels

1.2.1. Energy performance evaluation

Evaluating the energy performance of solar technologies requires robust and standardized key performance indicators (KPI). In recent years, several studies have focused on defining these KPI to better assess the efficiency of solar energy systems. This section presents insights from the IEA Task 66 in Bockelmann et al. (2022), specifically highlighting three main KPI from an energy performance perspective: load cover factor (LCF), supply cover factor (SCF), and on-site energy ratios (ER). The LCF is defined as the ratio between the solar self-used electricity and heat, and the total energy used for household and technical purposes in the form of heat and electricity. The SCF is the percentage of solar energy used on-site by the building over the total solar energy production. The on-site ER is the solar production response to the building's consumption.

1.2.2. Environmental impact assessment

Assessing the environmental performance of solar energy systems, including PV panels, ST, and hybrid PVT systems, focuses on key indicators such as CO2 emissions, Cumulative Energy Demand (CED), Energy Payback Time (EPBT) and materiel investment (Me), that are the most recurrent in the literature. Life Cycle Assessment (LCA) is the standardized tool used to evaluate the environmental impact of these systems, examining all life stages from material extraction to manufacturing, transportation, installation, operation, and recycling, furnishing the outputs that allows quantifying the KPI. The following aims to present a brief state of the art of studies that used LCA to quantify the four KPI chosen for the present work.

Kavian et al. (2020) used as indicator CO2 emissions of different types of PV panels: polycrystalline, monocrystalline, and thin-film cells, coupled with a ground source HP. The experimental data of the Fthenakis and Alsema (2006) study was used which indicated that the amount of climate change potential for the polycrystalline, silicon thin film, and monocrystalline are 37, 30 and 45 gCO2eq/kWh, respectively. In Nikolic et al. (2022), the CO2 emissions from photovoltaics are 50 g CO2 per kWh of generated electricity, whereas CO2 emissions from solar collectors are 72 g CO2 per kWh of generated thermal energy.

The CED is defined as the total primary energy consumed during the manufacturing, distribution and installation of the solar panel, defined in Frischknecht et al. (2015), with a distinction between non-renewable and renewable primary energy forms. From this value and the energy production of the solar panels, energy payback times are calculated. According to Bhandari et al. (2015), the average EPBT for various PV module types ranged from 1 to 4.1 years. The ranking of module types, from shortest to longest EPBT, is as follows: cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), amorphous silicon (a-Si), polycrystalline silicon, and monocrystalline silicon. The work of Bany Mousa et al. (2019) revealed that the EPBT of PV and ST panels ranged from 1.2 to 15 years across the various geographical locations considered. Additionally, the results indicate that a ST collector system has a lower EPBT in regions with high direct normal irradiation compared to a monocrystalline PV system.

Finally, a KPI named material investment, defined in Olivès et al. (2022) as the total quantity of material invested in the manufacturing and installation of the solar panel, is also evaluated in this work. According to their calculations using LCA and literature data, the material investment for an on-roof PV panel is approximately 5800 t/TWh. PV panels were compared to other energy production sources, such as solar power plants that require more than 9000 t/TWh of materials to generate electricity.

1.3. Research gap and motivation of the paper :

Comparing the performance of different solar technologies, especially concerning heat and electricity generation, using the energy metrics, may not adequately capture the full spectrum of their impacts, leading to incomplete assessments and potentially misguided conclusions. To avoid this problematic, three other metrics are used when trying to compare heat and electricity simultaneously, which are exergy, primary energy and energy equivalence, and each of these shows certain advantages and limitations. Concerning the environmental impact assessment, the normalized tool is the LCA, and solar technologies can be compared one to another by defining a functional unit (FU) usually taken as the kWh of energy produced, or the square meter. Following the first case leads to fall into the same problematic of dealing with both heat and electricity and comparing them in the same level.

The aim of this study is to address these challenges by evaluating the energy performance and environmental impact of the three solar technologies by establishing clear criteria and comparing the different ways of dealing with both heat and electricity. A case study application illustrates the assessment wherein PV, ST and hybrid PVT are evaluated and compared within the context of an individual house integration.

2. Method and development

2.1. Case study description :

2.1.1. Meteorological data

In this study, the solar panels are installed on an individual house's roof in the city of Chambéry in the south-east region of France. According to the Köppen climate classification, Chambéry experiences a mountain climate characterized by dry, hot summers and moderate winters. For the weather data, files are retrieved from the Meteonorm (2023) database v7.3.3 that uses interpolated data from other locations for both temperature and solar irradiation.

2.1.2. Solar panels technical and environmental description :

The selection of solar panels for this study was primarily based on the availability of detailed data sheets necessary for conducting energy simulations on TRNSYS, as well as the presence of environmental product declarations (EPD) required for environmental modeling on SimaPro. The EPD information was sourced from the French INIES (2023) database, which includes several PV panel references. For the solar ST collectors, only one EPD sheet was available, describing a generic flat-plate solar collector based on an analysis of eight commercial references. Since there was no EPD sheet available for a PVT panel in the INIES database, the international EPD system was consulted where only one reference for PVT was found.

The studied PV panel is a monocrystalline, monofacial, phosphorus-doped (P-type) module. Key characteristics summarized in tab.1 below, including nominal power, module efficiency, area, weight excluding mounting support and packaging, power temperature coefficient, lifespan, and degradation coefficient, were derived from the manufacturer's data sheets. Additional details such as wafer sizes and thickness, cell number, front and back sheet types, encapsulant, and frame material were obtained from the EPD of the PV panel available in the INIES database.

Tab. 1: Solar panels characteristics for energetic and environmental modeling

PV	
Nominal power at STC	450 W_p
Efficiency at STC	20.85 %
Gross area	2.16 m²
Total weight	24.20 kg
Power temperature coefficient	-0.35 %/K
Lifespan	25 years
Degradation coefficient 1st year	2 %
Degradation coefficient over lifespan	0.55 %
Wafer size	M10
Wafer thickness	150 μm
Cell type	Mono crystalline
Number of cells	60
Front sheet	Glass 3.2 mm
Encapsulant	EVA
Back sheet	PET
Frame	Aluminum

The flat plate solar collector consists of a flat absorber plate with liquid circulation that captures solar radiation, which is then transferred to the heat transfer fluid. This fluid circulates through the collector, transferring the absorbed heat for various applications. Its energy performance and environmental characteristics retrieved from the manufacturer and the INIES database respectively, are displayed in tab.2.

Tab. 2: Solar panels characteristics for energetic and environmental modeling

ST	
Nominal power	1364 W
Optical efficiency	77 %
Gross area	2.16 m²
a_1	3.71 $W.m^{-2}.K^{-1}$
a_2	0.015 $W.m^{-2}.K^{-2}$
Total weight	52.21 kg
Lifespan	50 years
Absorber	Aluminum / Steel
Tube network	Copper, coil
Frame	Aluminum
Insulation	Rock-wool
Working fluid	Brine

The PVT panel chosen is a second-generation PVT panel that offers a cutting-edge solution for simultaneously generating hot water and electricity. Featuring advanced technology, the panel maximizes solar radiation absorption and efficiently transfers heat through its lattice-like copper tube network. The 72-cell PV laminate produces electricity alongside thermal energy, while a transparent insulating cover and rock wool-insulated metal case minimize heat loss. The characteristics taken from the manufacturer and the EPD international system are summarized in tab.3 below.

Tab. 3: Solar panels characteristics for energetic and environmental modeling

PVT	
Nominal power at STC	350 W_p
Efficiency at STC	17.8 %
Gross area	1.96 m²
Total weight	52 kg
Power temperature coefficient	-0.36 %/K
Lifespan	25 years
Degradation coefficient 1st year	3 %
Degradation coefficient over lifespan	0.71 %
Wafer size	M2
Wafer thickness	210 μm
PV module	Laminate
Number of cells	72
Front sheet	Glass 3.2 mm
Optical efficiency	70 %
a_1	5.98 $W.m^{-2}.K^{-1}$
a_2	0 $W.m^{-2}.K^{-2}$
Absorber	Copper
Tube network	Copper, lattice-like
Frame	Aluminum
Insulation	Rock-wool
Working fluid	Brine

2.1.3 Building's energy loads :

The case study's building is a single-family detached house, modeled using the TRNSYS Type 56 building model as shown in figure 1. The house has a total area of 170 m², with 90 m² of heated space and a solar roof area potential of 16.6 m². It is assumed that two people live in the house, with a domestic hot water (DHW) consumption of 104 liters per day. From the simulations, the DHW annual needs reach $\boldsymbol{Q_{DHW}} = \mathbf{1478\ kWh}$ annually. The specific electricity profile was assessed using the CREST model v2.2.1 from McKenna and Thomson [2016], assuming an annual specific electricity needs $\boldsymbol{E_{elecspec}} = \mathbf{2280\ kWh}$. The air infiltration rate was set at 0.685 vol/h for the living rooms and 1.1 vol/h for the attic. The heating needs, that correspond to keeping a set point temperature of the heated areas at 19°C during winter and inter season, are equal to $\boldsymbol{Q_{SH}} = \mathbf{12492\ kWh}$ in Chambéry.

In order to make full use of the whole roof's surface, the solar panels installation cover all the 16.6 m^2 available area. Since each the PV and ST panels have a gross area of 2.16 m^2, the total number of panels installed for the two configurations is seven. The number of PVT installed is eight panels of 1.96 m^2 each. Regarding the house's energy systems, it is equipped with an air-to-water heat pump (HP), which serves as the sole heating system. Two storage tanks for the heating and DHW loops are connected to the heat pump and the heat exchanger of the ST and PVT panels. It is also assumed that the house is connected to the local electricity grid. Since the HP satisfies the heating loads, the energy consumption of the house when the solar energy produced is not sufficient is 100% electric and furnished by the grid $\boldsymbol{E_{grid}}$, and corresponds to the electrical consumption of the HP $\boldsymbol{E_{HPcons}}$ and $\boldsymbol{E_{elecspeccons}} = \boldsymbol{E_{elecspec}}$ the specific electricity consumption, with $\boldsymbol{E_{HPcons}} = \mathbf{6854, 6190}\ \boldsymbol{and}\ \mathbf{6426}\ \boldsymbol{kWh}$ annually in the three solar configuration, ie. PV, ST and PVT respectively.

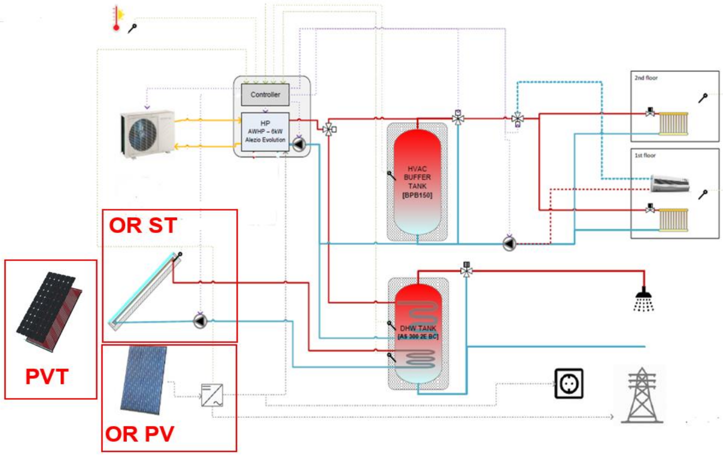

Figure 1: Building's energy systems configuration

2.2. Energy performance evaluation using the four metrics :

2.2.1. Solar self-produced and self-consumed energy :

From the TRNSYS simulations are retrieved the solar self-produced and self-consumed energy. The solar self-produced energy $\boldsymbol{E_{solar,tot}}$ corresponds to the total electricity and heat generated by the PV, ST and hybrid PVT. The solar self-consumed $\boldsymbol{E_{solar,used}}$ is the part of this produced energy that is locally used by the building to meet its demands. In the case of this study, the solar electricity is used to satisfy the specific electricity demand of the house when both the solar production and demand match. Solar electricity is also used to power the HP to satisfy the temperature set-points of the DHW and Buffer tanks. The solar over produced electricity is fed to the grid, which is not the case for the solar produced heat. The solar used heat is considered as the one stored in the two storage tanks, considering the thermal losses occurring in the primary solar circuit and the installation efficiency.

The three KPI from an energy perspective introduced in 1.2.1 and applied to the case study are defined following the equations 1, 2 and 3, and using the building's energy loads described in section 2.1.3 and the solar self-produced and self-consumed energy.

$$LCF_{En} = \frac{E_{solar,used} + Q_{solar,used}}{E_{solar,used} + E_{grid}} \quad \text{(eq. 1)}$$

$$SCF_{En} = \frac{E_{solar,used} + Q_{solar,used}}{E_{solar,tot}} \quad \text{(eq. 2)}$$

$$ER_{En} = \frac{E_{solar,tot}}{E_{elecspeccons} + Q_{SH} + Q_{DHW}} \quad \text{(eq. 3)}$$

2.2.2 Exergy evaluation :

The First Law of Thermodynamics allows combining different energy forms, but energy conversions and losses must be considered. The Second Law of Thermodynamics, introducing entropy, shows that not all energy transformations are reversible, causing inefficiencies.

Exergy is a state function that measures the maximum useful work that can be obtained from a system as it interacts with its environment. For the electrical part, exergy is equal to energy because electrical energy is seen as pure exergy. Whereas for the thermal part, exergy is defined as the maximum useful work derived from a system using the Carnot factor, which indicates the fraction of energy that can be converted into useful work in an ideal Carnot engine, where T is the temperature at which energy in heat form is supplied and T_{ref} is the reference temperature. Exergy depends on constant reference conditions like ambient pressure and temperature. However, for solar exergy evaluation, ambient conditions fluctuate, leading to different approaches in the choice of the reference temperature. In this work, exergy is evaluated on a daily basis, so the daily minimum temperature is taken as the reference temperature $T_{ref} = min(T_a(t))$ as in the work of Pons (2019).

$$\dot{E}x_{heat} = \dot{Q}\left(1 - \frac{T_{ref}}{T}\right) \quad \text{(eq. 4)}$$

Thermal exergy is assessed at many systems level. First is the solar heat exergy of the solar thermal and PVT heat production. The temperature T of the available solar heat production is the temperature at the outlet of the heat exchanger of the ST or PVT panel. For the heat produced by the heat pump, it is the outlet temperature at the condenser. For the space heating and domestic hot water heating loads, the available temperature is taken as the average temperature of the Buffer and DHW thermal storage tanks.

From these statements, the three KPI from an exergy perspective introduced in 1.2.1 and applied to the case study are defined following the equations 5, 6 and 7.

$$LCF_{Ex} = \frac{Ex_{solar,used}}{Ex_{solar,used} + E_{grid}} \quad \text{(eq. 5)}$$

$$SCF_{Ex} = \frac{Ex_{solar,used}}{Ex_{solar,tot}} \quad \text{(eq. 6)}$$

$$ER_{Ex} = \frac{Ex_{solar,tot}}{E_{elecspeccons} + Ex_{SH} + Ex_{DHW}} \quad \text{(eq. 7)}$$

2.2.3 Primary energy factor :

The main purpose of primary energy factors (PEF) is to provide a standard reference for calculating and comparing different energy sources, allowing diverse energy carriers like coal, natural gas, electricity, biomass, and uranium to be brought to a common basis as stated in Hirzel and al. (2023). In this work, PEF is used to convert the electricity from the grid into heat in the context of the french electricity mix. In France, the PEF for electricity is set at $\boldsymbol{\eta_{grid} = 2.3}$, this means that for 1 kWh of electricity in final energy, 2.3 kWh of primary energy are consumed on average. When it comes to renewable energy including solar energy, the PEF is equal to one.

Therefore, the three KPI introduced in 1.2.1 and applied to the case study are defined following the equations 8, 9 and 10, with the electricity imported from the local grid converted to the primary energy form using $\boldsymbol{\eta_{grid}}$.

$$LCF_{PE} = \frac{E_{solar,used} + Q_{solar,used}}{E_{solar,used} + E_{grid} * \eta_{grid}} \quad \text{(eq. 8)}$$

$$SCF_{PE} = \frac{E_{solar,used} + Q_{solar,used}}{E_{solar,tot}} \quad \text{(eq. 9)}$$

$$ER_{PE} = \frac{E_{solar,tot}}{E_{elecspeccons} * \eta_{grid} + Q_{SH} + Q_{DHW}} \quad \text{(eq. 10)}$$

2.2.4 Energy equivalence using the COP :

Another way to convert electricity into heat form, is to use a coefficient of energy equivalence that takes into account the use made of the solar produced electricity. The advantage of converting this solar electricity into heat will demonstrate the benefit of storing this electricity, for example in an electric car, through thermal inertia, or as in this case study, in hot water through the use of a HP. In this case study, solar electricity is used to fulfil the specific electricity needs of the house when both the solar electricity production and electricity needs match, and is also used to store hot water in the tanks for the DHW and heating needs through the use of a HP. The COP of the actual heat pump installed in the house is used to convert the part of the solar electricity into the heat form it is converted into by the HP. The COP is retrieved dynamically from the TRNSYS simulations as the ratio between the heat delivered and the electricity produced by the solar panels and consumed by the HP at every step of the simulation.

Therefore, the three KPI introduced in 1.2.1 and applied to the case study are defined following the equations 11, 12 and 13, with the solar electricity produced converted to the heat form using the COP of the HP.

$$LCF_{EE} = \frac{E_{solar,used} * COP + Q_{solar,used}}{E_{solar,used} + E_{grid}} \text{ (eq. 11)}$$

$$SCF_{EE} = \frac{E_{solar,used} * COP + Q_{solar,used}}{E_{solar,tot}} \text{ (eq. 12)}$$

$$ER_{EE} = \frac{E_{solar,tot} * COP}{E_{elecspeccons} + Q_{SH} + Q_{DHW}} \text{ (eq. 13)}$$

2.3 Environmental impact evaluation using SimaPro :

Life Cycle Assessment (LCA) is now a standardized approach for assessing environmental impacts of a product. The process starts with defining the goal and scope, which includes setting the purpose, boundaries, impact assessment method, and functional unit (FU) for the product under study. The next step involves conducting an inventory analysis by collecting data on the inputs and outputs throughout the product's life cycle stages. This is followed by an impact assessment, which converts the inventory data into environmental impacts. Finally, the results are synthesized and interpreted.

2.3.1 Goal and scope :

The goal of the LCA simulation is to provide the environmental footprint of the selected solar panel references, intended for installation in an individual house. This footprint assessment focuses on Global Warming Potential (GWP), Cumulative Energy Demand (CED), and material investment (Me) throughout the manufacturing, distribution, installation, and use phases. The SimaPro software and the Ecoinvent database v3.9 are utilized for this purpose. SimaPro and Ecoinvent are the most accurate tools in LCA due to their comprehensive database and rigorous data collection methods, ensuring reliable environmental impact assessments.

Among the various impact assessment methods available in LCA calculations, the environmental footprint (EF) reference package 3.1 is employed. This approach aligns with the EU Commission's recommendation 2021/2279, which aims to measure and indicate the environmental performance of products and organizations throughout their life cycle. The EF3.1 method uses the global warming potential over a 100-year time horizon (GWP100) to describe climate change potential. This indicator, expressed in kg.CO2-equivalent, is essential for assessing the environmental footprint of a system or product, as it evaluates its contribution to changes in global average surface-air temperature and subsequent impacts on climate parameters such as storm frequency, rainfall intensity, and flooding frequency. The CED is assessed using the abiotic depletion potential (ADP): fossil fuels indicator from the EF3.1 method, which considers only non-renewable energy resources in their fossil fuel form. Material investment, part of the LCA modelling, involves the materials utilized in manufacturing and installing the PV panels and excludes the material used for packaging. These materials are included in the life cycle inventory, which will be detailed subsequently.

The FU in which the LCA results are calculated in the LCA simulations is 1 kW of heat and electricity production capacity for the PV and ST panels whereas for the PVT, the LCA modelling is conducted for a FU of 1 module due to the data availability in the EPD sheet.

The final FU used to quantify the KPI and evaluate the impact of the solar panels as recommended is 1 kWh of heat and electricity produced. The initial FU in 1 kW is converted to kWh using the heat or electricity produced during the lifespan from the TRNSYS simulations following equations respectively. For the electricity generation, a degradation coefficient is taken into account with a maximum of 2% of production the first year and 0.55% the remaining years based on reference lifetime of 25 years with a mono crystalline PV panel. For the PVT panel, the degradation coefficient is equal to 3% the first year and 0.71% the remaining years until the lifespan of 25 years. No degradation coefficient is considered for the heat production of the ST and PVT systems. The lifespan of the ST system is considered 50 years. The scope of the LCA modelling takes into account an inverter replacement after 15 years as well as all the other equipment that come alongside a PV installation, i.e. the BOS.

$$E_{solar,lifespan} = E_{solar,tot} * D_{1^{st}year} * \left(1 + \sum_{n=1}^{Lifespan-1} \left(1 - D_{Lifespan-1}\right)^{n}\right) \text{ (eq. 16)}$$

$$Q_{solar,lifespan} = Q_{solar,tot} * Lifespan \text{ (eq. 17)}$$

Then, the second FU is 1kWh of useful produced solar exergy, which as stated in section 2.2.2 is the total solar electricity produced during the lifespan $E_{solar,lifespan}$ since electricity is pure exergy. For the solar thermal part, $Ex_{solar,lifespan}$ is calculated following equation 4. The last FU corresponds to 1kWh of equivalent produced solar electricity using the COP from the HP as explained in section 2.2.4. Note that it is unnecessary to study a FU of PE, since as mentioned above the primary energy factor for solar energy is equal to 1.

2.3.2 Life cycle inventory :

At this stage, all processes necessary to create the final product are integrated to design the product stage. This involves selecting processes for the manufacturing phase, followed by the processes related to distribution and installation, as well as compiling an inventory of materials invested in the manufacturing and installation mi, both displayed in tab.4 and tab.5 respectively.

Tab. 5: Solar panel's manufacturing processes

Solar technology	LCA step	Ecoinvent process	Location
PV	Polysilicon	Siemens process	Germany
	Ingots	Czochralski purification	Norway
	Wafers	Diamond wire cutting	Norway
	Cell	PERC process	China
	Module assembly	Monofacial	France
	Distribution	Lorry	Chambéry
	Installation	Neglected	Chambéry
ST	Absorber	Laminated + Laser welding	France
	Frame	Laminated	France
	Coil	High pressure tube twisting	France
	Collector assembly	Manually	France
	Distribution	Lorry	Chambéry
	Installation	Neglected	Chambéry
PVT	PV module	PV laminate	China
	ST heat exchanger	Same process as ST	Spain
	Assembly	Manually	Spain
	Distribution	Lorry	Chambéry
	Installation	Neglected	Chambéry

Tab. 4: Material invested mi in kg per functional unit.

PV		ST		PVT	
Silver	0.014	Aluminium	19.4	PV laminated	17.80
Copper	2.7	Steel	7.4	Heat recovery system	4.65
Aluminium	18.1	Copper	2.1	Steel (Housing)	9.4
Steel	0.62	Silicone	0.72	Rock-wool	2.88
Silicon	2.6	SMC	1.2	Glass	15.10
Glass	39.2	PELD	0.26	EVA	0.64
Plastic	6.7	Polyester	0.19	PVC	6.12
		PVC	0.07	Silicone	0.83
		EPDM	0.26		
		EPS	0.13		
		PA66	0.06		
		Glass	13.6		
		Rock-wool	2.2		
Total (kg)	**69.9**	Total (kg)	**47.6**	Total (kg)	**57.4**

The manufacturing scenario of the PV panel described is retrieved from internal CEA database and is typical in the market, where the silicon manufacturing phases are carried out in Germany and Norway, given the presence of plants specializing in these processes in these countries as said in Norman, (2023). Most PV panel cell assemblies are still commonly done in China due to the cost advantages offered by Chinese manufacturers. Finally, to cater to local markets, the assembly of the PV module is conducted in the installation country. Note that the transport between the different manufacturing is taken into account in the PV panel modeling. The materials comprising the PV panel include those used in both the manufacturing of the panel and its installation on the roof. Tab. 4 displays the quantity of materials per functional unit of 1 kW. The quantities of aluminum, steel, and copper used for mounting and roof installation of the PV panels are sourced from Underwood et al. (2022), using the average of the ranges considered for roof-mounted modules for each material. Glass constitutes the largest share of material use in a PV panel since the module considered is dual glass, enhancing its toughness and resistance. The second most used material is aluminum, utilized for the frame, support, and mounting structures. Plastic is used for both the encapsulant and back sheet. Copper is used for interconnecting the cells, in the junction boxes that are part of the BOS, in the inverter's composition, and for module-to-module cabling. Additionally, the inverter contains steel, and silver is used in the cell for its conductive properties.

Solar thermal collectors have the advantage of requiring simpler industrial processes than PV, which leads to their entire manufacturing in Europe. For the solar thermal collector selected in this study, all manufacturing and assembly stages are carried out in a factory in France, where all the collector's parts, i.e. the absorber in the form of rolled aluminum plate, the copper tubes for the exchanger, and the glass, are shipped. Raw materials extraction and pre-processing is included in the materials inventory, with materials of European origin considered whenever possible as in the case of aluminum, or by default a global or rest-of-the-world origin is considered.

The PVT manufacturing comprises both the PV part that consists of a laminated PV module, the heat recovery part for the thermal production that is constituted the same way as the flat plate collector of an aluminum absorber where copper twisted tubes are welded on. The PV laminate originates from China where it is manufactured, and the heat recovery part is manufactured in a factory in Spain. The two parts are then brought and assembled together in a Spanish factory and shipped to the installation place in France.

2.3.3 Life cycle impact assessment (LCIA) :

The LCA outputs from the SimaPro simulations and that are discussed in the following are the global warming potential (GWP) in kg.CO2eq and the non-renewable cumulative energy demand (CED) in MJ and are displayed for the whole manufacturing, distribution and installation phases, per initial FU of 1 kW for the PV and ST, and a FU of 1 module for the PVT.

Tab. 6 : LCA simulation outputs for the FU.

Per FU = 1kW of PV/ST, or 1 PVT module	PV	ST	PVT
GWP in kg.CO_2eq	943	385	724
CED in MJ	11723	4610	13664

These simulation output results are intermediate results that will allow to quantify the environmental KPI described in the following :

- The energy payback time (EPBT) expressed in years is a frequently used indicator. It refers to the period it takes for a solar panel to generate the same amount of energy that was spent in its manufacturing, transportation, installation, and maintenance processes. Therefore, the EPBT is expressed as follows in equation 14 :

$$EPBT = \frac{CED}{E_{solar,tot}} \quad \text{(eq. 14)}$$

- The quantity of materials Me employed to deliver 1 kWh of electricity and/or heat for the solar panels is equal to the ratio between the total quantity of material invested in the manufacturing and installation obtained from the LCA in the inventory analysis mi and the energy production over the lifespan of the panel following equation 15.

$$Me = \frac{m_i}{E_{solar,lifespan}} \quad \text{(eq. 15)}$$

2.4 KPI quantification : application to the case study

2.4.1 Energy performance KPI:

The energy performance KPI introduced in section 1.2.1, ie. the load and supply cover factors and the on site energy ratio, are quantified following the case study of the individual house with the three different solar configurations coupled with an air-to-water HP. In literature, it was seen that the three KPI are defined mixing heat and electricity as in equations 2, 3 and 4. The objective of this work is to define these KPI also using either exergy or converting electricity to heat form using either the french PEF or the COP of the studied HP. The different definitions are displayed following equations 5 to 13. In table 8 are displayed the results of the KPI quantification in the three solar configurations and using the four metrics, ie. Energy (En), exergy (Ex), primary energy (PE) and energy equivalence (EE).

Tab 8. : Energy performance KPI quantification applied to the case study

	LCF [%]			SCF [%]			ER [%]		
	PV	**ST**	**PVT**	**PV**	**ST**	**PVT**	**PV**	**ST**	**PVT**
En	15.3	30.4	30.1	34.7	89.1	54.2	22.3	22.4	33
Ex	15.3	25.4	26.6	34.7	89.1	51.7	16.9	13.6	22.5
PE	5.7	16	13	34.7	89.1	54.2	11	11.6	16.6
EE	15	17.4	21	46.1	89.1	57.5	18.5	12.3	22.1

The solar panels scored LCF equal to 15.3%, 30.4% and 30.1% for the PV, ST and PVT respectively in the energy definition, meaning that the solar energy used is up to 30% for PVT and ST of the total energy used on site, which consists of electricity imported from the grid when solar energy is not sufficient. What justifies these values is that the ST and PVT solar used energy is higher than the PV due the solar heat storage. When using the exergy definitions, the ST and PVT LCF are lower because of the maximum useful work that can be extracted from the solar heat produced and stored, still their LCF is higher than the PV. When converting the electricity from the grid into its primary energy form in the denominator, the LCF values for all the three solar panels is reduced. Finally, in the case of converting the electricity produced by the PV and PVT panels into heat via the heat pump, the LCF values are increasingly close for all three panels, suggesting that this metric could enable a fairer comparison.

The SCF values, meaning the share of solar energy produced that was consumed on site, show that the ST offers the most solar self-consumed energy reaching 89.1% because the heat is stored in the thermal tanks, in the four definitions since the temperatures involved are the same in the case of the produced heat and the consumed one. In the PV case, the SCF reached 34.7%, meaning that only this share was used to respond to the specific electricity demand when it matched the electricity production, and the demand of the HP. The rest is injected into the local electricity grid. This valued remained the same for the three definitions, ie. the energy, exergy and primary energy factor one, since electrical energy is pure exergy and the PEF of solar PV electricity is equal to one. As for the energy equivalent definitions, that reached 46.1%, it is due to the conversion of the PV electricity used by the HP to the actual heat produced by the HP using the COP dynamically. The PVT panel's score in SCF falls between both the PV and ST thanks to its ability to combine flexible electrical generation and storable heat.

Unlike the LCF, the on-site ER, or solar fraction as it is known in many studies, accounts for the contribution of solar energy in its response to the building's energy needs. In this case study, the building's needs consists of the space heating, the DHW and specific electricity needs. In the nominator, the 16.6 m^2 of the PV and ST panels produced almost the same amount of electricity and heat, resulting in a LCF nearly equal to 22.3 and 22.4% respectively. The PVT produces 30% more energy than the PV and ST for the same surface, resulting in an ER of 33%. In terms of exergy, the same tendency is observed, which devalues heat in comparison to electricity due to their different exergetic nature and content. The values of on-site ER all decrease in the case of the primary energy and energy equivalence definitions, because the electricity imported from the grid and converted to heat form, whether using the primary energy factor or the COP, is greater.

2.4.2 Environmental impact assessment KPI :

The environmental impact KPI results are displayed in table 9, for the three solar solar panels, and per FU of 1kWh of produced energy, useful exergy and energy equivalence.

In terms of energy, the ST collectors scored the lower GWP equal to 17.7 of kg.CO_2eq per kWh of heat produced, against 31.1 for PV and 52.3 for PVT. ST require manufacturing processes that are less energy consuming and occurring in Europe, unlike PV and PVT modules which are produced in China. When using the exergy metric, the impact of ST and PVT are increased, but ST still does not exceed PV. By considering the share of solar electricity converted into heat by the heat pump and stored, as the production actually served by PV and PVT panels, their environmental impact in terms of all the environmental KPI is further reduced. In summary, ST is the most environmentally and energetically efficient system overall, but PV offers a material efficiency advantage in heat-equivalent applications. PVT, while offering both electricity and heat, tends to have the highest environmental and material costs, indicating that it may not be the best option unless its dual-output capabilities are highly valued.

Tab 9. : Environmental impact KPI quantification

Per FU = 1kWh	**GWP [kg.CO_2eq]**			**CED [MJ]**			**EPBT [years]**			**Me [t/TWh]**		
	PV	ST	PVT	PV	ST	PVT	PV	ST	PVT	PV	ST	PVT
En	31.1	17.7	52.3	0.39	0.21	0.66	0.8	0.5	1.4	2306	2184	2510
Ex		22.7	59.2		0.27	0.74		0.6	1.6		2803	2843
EE	23.8	17.7	46.1	0.29	0.21	0.58	0.6	0.5	1.3	1762	2184	2212

While the analysis highlights Solar Thermal (ST) as the most efficient and environmentally friendly option overall, and Photovoltaic (PV) as the most material-efficient for heat-equivalent energy, it is important to acknowledge a limitation in the study. The PVT system analyzed represents only one industrial reference, whereas the PV and ST systems are based on average panels. This means that the performance of PVT in this study might not fully reflect the diversity of PVT technologies available on the market, which could potentially offer different efficiency and environmental profiles. Therefore, the conclusions drawn about PVT may be limited in scope and may not capture the full potential or variability of this technology.

3. Conclusion and perspective

In the context of global climate crisis, using solar energy in residential buildings emerges as a crucial solution due to resource availability and technological maturity. To compare various solar technologies fulfilling the building needs, a standardized assessment of their energy and environmental performance is imperative. This study focuses on evaluating active solar panels' energy and environmental performance, considering their electricity and heat outputs, and compares different metrics of defining the KPI based on energy, exergy, primary energy, and energy equivalence. While primary energy reduction factor is commonly used, it remains dependent on the location when choosing the electricity to heat conversion factor. The second law of thermodynamics introduces exergy as a key metric, dependent on the choice of reference temperature, and allows considering the quality of the energy compared to first law of thermodynamics. Converting solar energy production and building loads using energy system's COP reveals promising comparisons, necessitating further investigation concerning the choice of the energy system. Integrating both energy forms facilitates future comparisons across economic, technical, and social criteria, paving the way for informed solar panel selection in building applications.

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