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Life Cycle Assessment of solar energy systems for the provision of heating, cooling and electricity in buildings: A comparative analysis

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A B S T R A C T

A detailed Life Cycle Assessment (LCA) "*from cradle to grave*" is performed to a solar combined cooling, heating and power (S-CCHP) system that provides space heating, cooling, domestic hot water and electricity, following two different methodologies (the ReCiPe 2016 Endpoint (H/A) v1.03 and the carbon footprint IPCC 2013 100 years). The innovative S-CCHP system is currently in operation in an industrial building located in Zaragoza (Spain), and the transient model developed to estimate the annual energy outputs has been validated. The system consists of hybrid photovoltaic-thermal (PV-T) collectors integrated via two parallel thermal storage tanks with an air-to-water reversible heat pump (rev-HP). Another contribution is that the detailed LCA analysis is also performed to a conventional PV-system and a grid-based system, viz building electricity consumption supplied from the grid (baseline configuration). The results show that the proposed S-CCHP system has half of the environmental impact of the grid-based system, according to the ReCiPe 2016 Endpoint (H/A) and the IPCC GWP 100a methods (4.48 kPts *vs* 8.87 kPts, and 82.4 tons of $CO_{2\ eq}$ *vs* 166.9 tons of $CO_{2\ eq}$, respectively). The PV-system has 30% less environmental impact than the grid-based system. Another novelty and contribution are the sensitivity analyses performed to assess the influence of the system lifetime, the solar irradiance and the power generation mix (also known as the electricity mix) on the LCA results. The results show that the proposed S-CCHP system appears as an up-and-coming alternative to reduce the environmental impacts of buildings in all the considered solar irradiance levels and electricity mix scenarios, even in climates with low irradiance levels or in countries with a highly decarbonised electricity supply.

1. Introduction

Two of the core objectives driving the energy supply towards decarbonised energy systems are i) securing the energy supply and ensuring the reliable provision of energy; and ii) improving sustainability by reducing GHG emissions, pollution, and dependence on fossil fuels [1,2]. The energy union strategy aims at providing consumers with secure, sustainable, competitive and affordable energy [2]. To achieve this, the EU has formulated a low-carbon economy roadmap as a pathway towards reducing emissions by 2050 through commitments without disrupting energy supplies [3]. The roadmap includes, among other initiatives, an increase in the uptake of renewable energy sources (RES) as a fundamental pillar in the ongoing energy transition.

Heating and cooling (H/C) is the largest energy end-use sector in Europe, ahead of transport and electricity [4]. H/C in buildings and industry accounts for half of the EU energy consumption (983 Mtoe in 2019) [5]. Most of the building heat demand is for space heating (52%), process heat (30%) and water heating (10%). The demand for space cooling is still small but fast-growing [6]. However, at present, the vast majority of H/C is still generated from fossil fuel combustion, with only 22% generated from RES (in 2019) [5], the majority of which is from biofuels and renewable waste [5]. In this context, the development and implementation of RES for building H/C are essential for displacing fossil fuel utilisation, and thus reducing the associated GHG emissions.

Solar energy can contribute to both the electrical and thermal demand of buildings using photovoltaic (PV) and solar thermal technologies, respectively. Therefore, solar heating and cooling (SHC) technologies appear as an attractive decarbonisation alternative. Different types of solar thermal collectors (e.g. flat plate, evacuated tube, parabolic through) can be used to harvest solar energy in SHC systems [7-11]. Alternatively, PV systems can be coupled to heat pumps (HP) in solar-assisted heat pump (SAHP) systems for solar heating [12-14] and solar cooling [15].

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Nomenclature

Abbreviations

a-a	air-air
a-w	air-water
COP	Coefficient of performance
DHW	Domestic hot water
EC	European Commission
EPBT	Environmental payback time
EU	European Union
EVA	Ethylvinylacetate
GHG	Greenhouse Gases
GWP	Global Warming Potential
HP	Heat pump
H/C	Heating and cooling
IPCC	Intergovernmental Panel on Climate Change
ISO	International organization for standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
PBT	Payback time
PE	Polyethylene
PP	Polypropylene
Pts	Points in ReCiPe methodology
PV	Photovoltaic
PVC	Polyvinyl chloride
PVT	Photovoltaic-thermal
RES	Renewable energy sources
rev-HP	Reversible heat pump
RoW	Rest of the world
SAHP	Solar assisted heat pump
S-CCHP	Solar combined cooling heating and power
SHC	Solar heating and cooling

Symbols

G''	Net solar irradiance
η_e	Electrical efficiency
η_{th}	Thermal efficiency
T_a	Ambient temperature
T_{fm}	Mean fluid temperature
T_r	Reduced temperature
T_{PV}	PV temperature
T_{ref}	Reference PV temperature
u	Wind speed

In recent years, hybrid photovoltaic-thermal (PV-T) collectors have been gaining attention both in research and applications. PV-T collectors are particularly attractive for applications in constrained spaces (e.g. in densely populated areas), because PV-T collectors generate both electricity and useful heat simultaneously from the same aperture area [16], with higher overall efficiency than the separate PV and solar thermal systems [17-19]. In addition, the integration of PV-T collectors with H/C technologies has the potential to cover a significant fraction of the energy demand of buildings, as it allows for the simultaneous generation of electricity, heating and cooling [20,21].

Some studies integrate concentrated PV-T [22-25], air-based PV-T [26-29] and water-based PV-T collectors [20,30-32] with H/C technologies. Previous research concluded that solar combined cooling, heating and power (S-CCHP) systems based on PV-T collectors could cover more than 60% of the combined heat demand for space heating and domestic hot water (DHW), along with more than 50% of the cooling needs of households, with reasonable installation areas [33,34]. This work focuses on the LCA of PV-T collectors integrated with heat pumps.

Kamel and Fung [28] studied an air-based PV-T collector coupled with air-source HP, where the warm air generated in the air-based PV-T acted as the source of heat production. These authors concluded that a significant reduction in the electricity costs to run the HP could be achieved thanks to this integration with PV-T collectors. The low density and small heat capacity of air limit improvements in the air-based PV-T collector performance, although this type of collector is attractive in applications where water is in limited supply [35].

Other authors proposed the integration of refrigerant-based PV-T collectors with HPs, which can maximize the solar energy utilization and, at the same time, enhance the COP of the HP [36,37]. In such integration, the heat produced by the PV-T collectors is used as the source of an HP [38] to provide space or water heating. For instance, previous authors [39] concluded that almost all the required heating loads in the winter months in Nanjing and Hong Kong (China) could be met using a PV-T-HP system with a variable speed compressor. Zhang et al. [40] analysed the economic performance of a solar photovoltaic/loop-heat-pipe and HP system for domestic heating and concluded that local utility prices and renewable incentives are critical for the financial feasibility of these systems. Recently, some authors proposed the integration of a roll-bond PV-T collector as the evaporator of a single-stage compression HP for the provision of heat and power in northern China during summer [41].

Reversible HPs (rev-HP) can also be integrated with the thermal output of water-based PV-T collectors [42], increasing the COP in the heating mode in winter [34,43], while in summer, the electrical output generated by PV-T collectors can be used to run the HP to provide cooling [34]. For instance, a water-based PV-T collector integrated with a water-to-water HP to provide space heating and electricity to households was recently proposed [44]. The results showed that increasing the flow rate enhances the total PV-T collector efficiency as also does it increasing the size of the storage tank [44]. Other investigators [45] analysed the performance of a dual indirect SAHP system, with the PV-T collector acting as the evaporator and connected in parallel with an air-source HP, operating simultaneously. The results showed that the PV-T evaporator could compensate for the performance degradation of the air-source evaporator caused by the increasing condensing temperature, while the air-source evaporator could recover heat under low radiation levels [45]. Other studies [12] analysed and compared four alternative SAHP heating systems and concluded that for high electricity prices, PV-T collectors integrated with a water-source HP seemed the best alternative [12]. Water-based PV-T collectors with micro-channels as thermal absorber have also been proposed in the literature. The experimental results of a PV-T collector integrated with water-source HP showed COPs of 3.2 in heating operation mode [46].

There are several environmental-impact analyses of solar thermal [47,48] and PV-T systems [49,50]. However, most of the previous studies assess the environmental payback time (EPBT) [51] and/or the CO_2 emissions [52-56], while there are very few studies that perform a complete Life Cycle Assessment (LCA) [57-60]. A recent review [50] concluded that, while some of the works follow the standard ISO procedure for LCA, the method followed is less transparent in most of them. Also, some studies do not include references for the LCI data sources. The review also concludes that there is a lack of studies addressing the industrial production of PV-T collectors. Several authors estimated the EBPT and the CO_2 emissions of water-based PV-T collectors, obtaining an EPBT of 4–14 years, depending on the balance of system requirements and the electrical efficiency [52,53]. In a similar analysis [56], the authors conclude that free-standing PV-T systems have a lower EPBT than building-integrated PV-T. More recently, a life cycle exergy analysis of three configurations of nanofluids-based PV-T systems has been performed, estimating the exergy PBT and CO_2 emissions avoided,

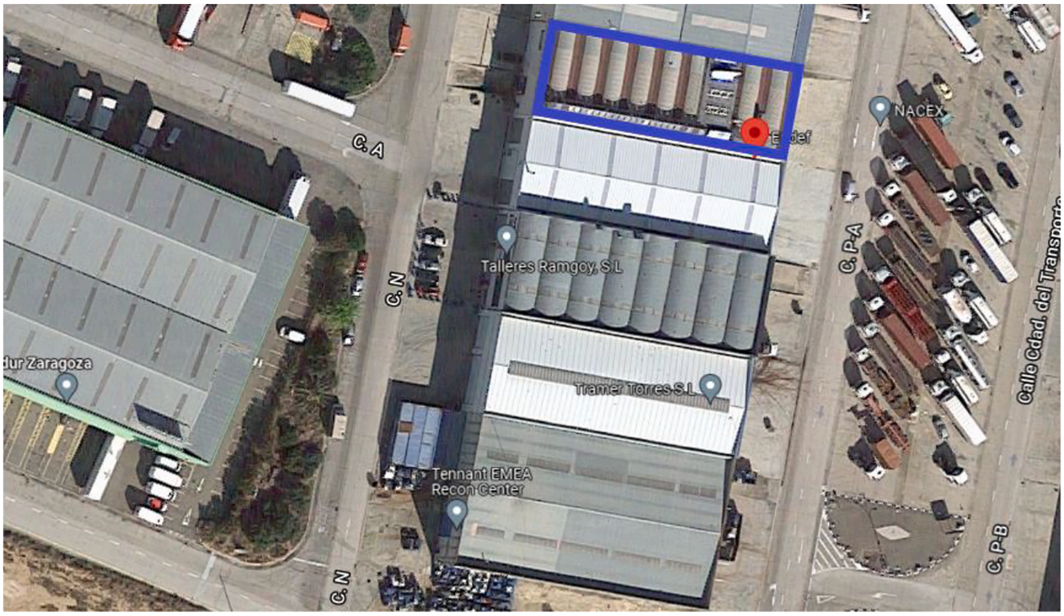

Fig. 1. Aerial view of the industrial building under study, marked in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Annual energy demands of the industrial building under study.

Description	DHW	Space heating	Space cooling	Electricity
Schedule	Mon – Fri (8–18 h)	Mon – Fri (8–18 h)	Mon – Fri (8–18 h)	Baseload (24 h/day) + Higher consumption Mon – Fri (8–18 h)
Temperature (°C)	60	30–35	7–12	
Annual demand (kWh/year)	2353	9686	8936	12,838

Table 2
Efficiencies of the components and annual energy consumption in the grid-based system.

Description	DHW	Space heating	Space cooling	Electricity
Temperature (°C)	60	30–35	7–12	
Boiler efficiency/rev-HP COP	0.98	2.36	2.03	–
Electricity consumption (kWh/year)	2401	4104	4402	12,838

and the results have been compared with standard PV and PV-T systems [54].

Wang et al. [61] performed an LCA study of a basic natural gas CCHP integrated with PV and/or solar thermal collectors, assessing three impact categories: global warming potential, acidification potential and respiratory effect potential. Meanwhile, Carlsson et al. [48] undertook an LCA on solar thermal systems based on flat-plate and evacuated tube collectors. None of these studies considers PV-T collectors. Other authors developed a simplified LCA tool to calculate life cycle energy and environmental balances of SHC systems [62]. The tool includes conventional solar thermal collectors (e.g. flat-plate and evacuated tube collectors) or PV modules to harvest solar energy. Recently, Blanco et al. [63] proposed the integration of LCA into energy system models (ESM) to allow evaluating alternative policies, capacity evolution, environmental impacts and energy economics in an integrated way. The authors applied this method for Power-to-Methane in the EU.

A recent review [50] concluded that the number of studies on the environmental impact of PV-T collectors and systems is still small. From the previous works, most of the systems are active water-based PV-T systems for DHW supply [49,57]. Previously, an energy and environmental assessment of an air-based PV-T system was performed using SimaPro 5.1 software [60]. The environmental indicators were calculated for all the life cycle phases, from raw material extraction to end-of-life disposal, and included the global warming potential for a time horizon of 100 years (GWP100) and the primary energy resources consumption [60]. A similar analysis was performed by the same authors [64] with water-based PV-T collectors, analysing unglazed, glazed PV-T collectors, horizontal or tilted, and with or without reflector, and the results were compared with a PV system. The LCA results underlined that, compared to a conventional PV module, the higher energy production of the PV-T collectors due to the thermal energy generation compensates for the increased impacts due to the additional components, leading to lower energy and CO_2 payback times [60,64].

A recent study [58] performed an LCA of a PV-driven rev-HP system installed in a 100 m^2 residential building in Milan (Italy). The results were compared with conventional H/C alternatives, including separate production of electricity and heat grid-connected HPs and solar absorption systems. The study estimates emissions amounting to 71.8 kg/MWh equivalent CO_2 for the PV-driven rev-HP, and 150.4 kg/MWh equivalent CO_2 for the solar absorption system [58]. Another recent investigation proposes a multi-objective optimization with LCA on S-CCHP systems based on concentrated PV-T and a gas turbine installed in a hotel building. The environmental impacts analysed include global warming potential, acidification potential and respiratory effect potential. The optimisation results show that the optimum hybrid system that minimises the aforementioned environmental impacts is based on partially (39%) covered PV-T collectors [59].

The main contribution of this work is to fill the gap in the literature of detailed LCA of S-CCHP systems based on PV-T collectors and their comparison with conventional technologies for the energy provision in buildings. The main novelty is that the LCA is performed "*from cradle to grave*" following two different methodologies, the ReCiPe 2016 Endpoint (H/A) v1.03, to cover a wide range of 22 environmental impact categories, and the carbon footprint IPCC 2013 100 years due to the social relevance of global warming. Furthermore, another novelty is that this analysis is performed in an innovative S-CCHP system proposed by the authors in previous research [65-67], which is currently in operation in

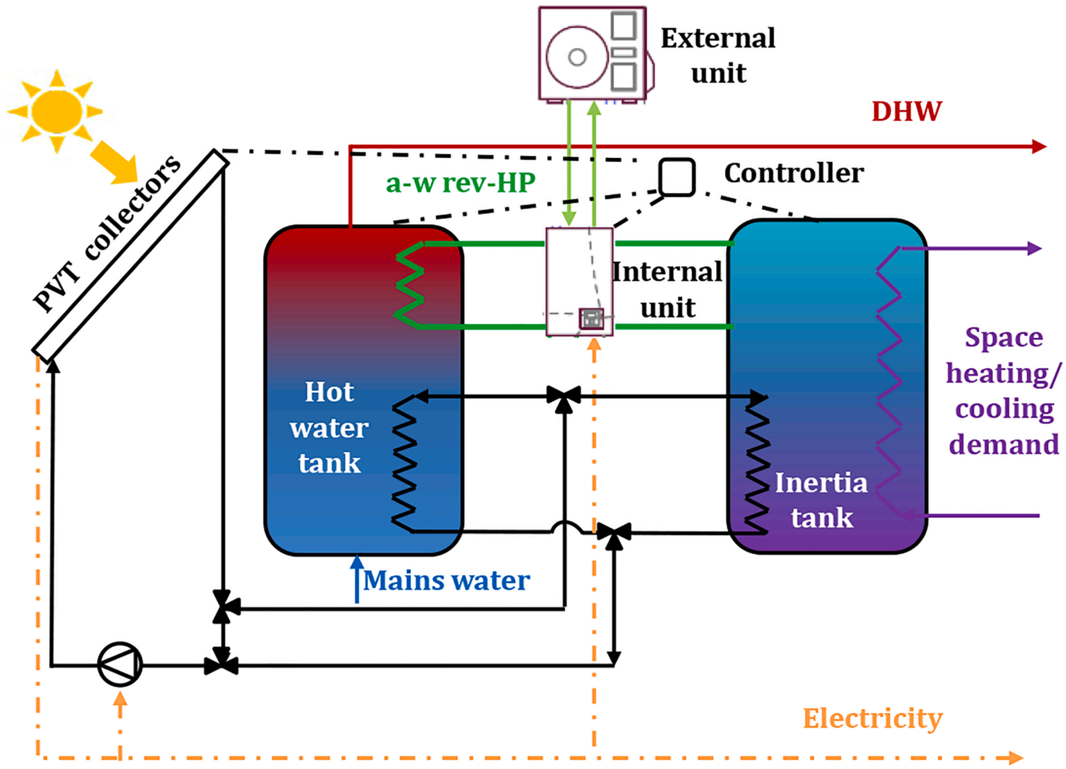

Fig. 2. Schematic diagram of the proposed S-CCHP system.

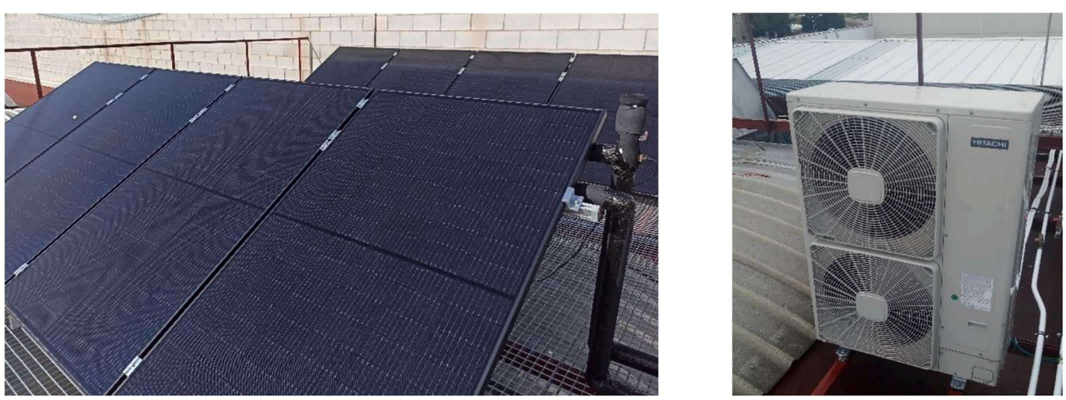

Fig. 3. Photos of the PV-T collectors (left) and the external unit of the rev-HP (right) installed on the roof of the industrial building. Photos facilitated by EndeF [68].

an industrial building (EndeF Solar Solutions facilities [68]) located in Zaragoza (Spain). The system provides space heating, cooling, DHW and electricity [67]. The proposed S-CCHP system consists of PV-T collectors integrated via two parallel thermal storage tanks with an air-to-water rev-HP. The transient model developed to estimate the annual energy outputs of the proposed S-CCHP system has been already validated [66]. Another contribution is that the detailed LCA analysis is also performed to a conventional PV-system and to a grid-based system (building electricity consumption supplied from the grid, baseline configuration), to compare the results of the different assessed systems. A further novelty and contribution of this work is the sensitivity analysis performed to assess the influence of the system lifetime, the climate, and the power generation mix (also known as the electricity mix) on the LCA results. The main benefit of the proposed methods is to allow the comparison of different system configurations in a diverse set of scenarios considering a wide range of environmental impact categories with the ReCiPe method (considering human health, ecosystem quality and resource scarcity), as well as the carbon footprint which has a critical relevance due to global warming.

This work is structured as follows: Section 2 includes a description of the system configurations analysed in this research, along with a detailed description of the LCA methodology followed. Section 3 details the life cycle inventory (LCI) of the system configurations (Section 3.1), the energy balance during the operation phase for the system configurations in the different climates (Section 3.2) and the life cycle assessment results (Section 3.3). Finally, Section 4 further discusses the results and reports the main conclusions.

2. Methodology

The solar systems are modelled in the dynamic simulation software TRNSYS [69], where the building's real heating, DHW, cooling and electricity demands are used as inputs to the model to perform transient simulations with a 15-min time-step for one year. Several system configurations are analysed (see Section 2.1) in the current location. The LCA is performed following ISO standards 14040 and 14044 [70,71],

Fig. 4. Photos of the DHW tank (left), the inertia tank (middle) and the internal unit of the rev-HP (right) installed on the first floor (at the end of the corridor of the office area) of the industrial building. Photos facilitated by EndeF [68].

using the SimaPro 9.0.0.49 software [72] and the Ecoinvent v3.5 database [73] (see Section 2.2). The building energy demand is the same in all the scenarios considered below.

2.1. System configurations

The proposed S-CCHP system, based on PV-T collectors and an air-water reversible HP (rev-HP), is currently installed and in operation (see Section 2.1.4) in an industrial building (EndeF Solar Solutions facilities [68]) located in Zaragoza (Spain) that has DHW, space heating, cooling and electricity demands (see Section 2.1.1). This work also compares this system with two alternative ones: a grid-based system (see Section 2.1.2) and a conventional PV-system (see Section 2.1.3).

2.1.1. Building energy demand

The industrial building consists of two main areas: a manufacturing area and an office area. The office area has two floors, a ground floor that is composed of an open space area and a seminar room; and an upper floor divided into three offices, a meeting room, toilets, and a changing room. The manufacturing area is a single open-space floor with high ceilings. The building is a semidetached industrial unit, with the entrance facing East (see Fig. 1). The manufacturing area demand includes lighting and electrically powered devices and equipment. The office area has a demand for space heating in winter and for space cooling in summer. This area also demands DHW for toilets and showers and includes demands for lighting and small electrical devices (e.g. computers, printers, etc.), as well as a small kitchen.

Table 1 shows the actual energy demand of the building provided by EndeF [68], including DHW, space heating through fan-coils (30–35 °C), space cooling (7–12 °C) and electricity consumption (for lighting and electrical devices).

2.1.2. Grid-based system

Before installing the proposed solar system, the industrial building had an air-to-air rev-HP to provide space heating and cooling, powered by electricity from the grid, and DHW was satisfied with an electrical heater. The total electricity consumption of the industrial building was 23,745 kWh, of which 10,907 kWh (46%) was electricity to cover the thermal (hot and cold) energy demand (see Table 2). This has been considered the baseline configuration to compare with the proposed solar system.

2.1.3. PV-system

The conventional PV-system consists of 16 PV panels of Trina Solar (Honey Black TSM-320-DD06M.05) [74], with a total power capacity of 5.12 kW (27.2 m^2) and a nominal electrical efficiency of 18.8%, that feed the air-to-air rev-HP that was previously installed in the building (COP of 2.36/2.03 for space heating/cooling). A 5 kW inverter is also used (Fronius Symo) [75]. In this configuration, the total electricity consumption of the industrial building is the same as in the baseline configuration (see Table 2), because the same heat and cold delivery components are used (the air-to-air rev-HP for space heating/cooling and the electrical heater for DHW).

2.1.4. S-CCHP system

The proposed S-CCHP system is composed of PV-T collectors, an a-w rev-HP, two parallel storage tanks, the hot-water tank to satisfy DHW demand, and the inertia tank to satisfy the space heating or cooling demands. Depending on the temperature of the tanks and of the PV-T collector, the thermal output of the PV-T collectors is directed to one of the two tanks through an active closed-loop system with a bypass valve controlled by a differential temperature controller (Fig. 2). When there is cooling demand, water circulates through the PV-T collectors at night to cool the water in the inertia tank (radiative cooling). In all cases, the rev-HP acts as an auxiliary heater/cooler to reach the set-point temperatures of the building thermal demand. The PV-T collectors electrically power the rev-HP, and the PV-T electrical output not consumed by the rev-HP is used to match the building electricity demand. The main system components (PV-T collectors, storage tanks, rev-HP) are implemented in the model by modifying the corresponding TRNSYS TYPES to match the real characteristics and performance of the commercial units [65]. Details of the energy modelling of this system in TRNSYS can be found in previous research by the authors [65,66].

The S-CCHP system consists of 16 uncovered PV-T collectors (5.12 kW, 27.2 m^2) manufactured by EndeF [68] with the thermal (η_{th}) and electrical (η_e) efficiencies shown in Eqs. (1–2) (provided by the manufacturer [68]),

$$\eta_{th} = 0.377\cdot(1 - 0.030\cdot u) - (9.71 - 0.098\cdot u)\cdot\left(\frac{T_{fm} - T_a}{G^{"}}\right) \tag{1}$$

Table 3
Efficiencies of the components and annual energy consumption in the proposed S-CCHP system.

Description	DHW	Space heating	Space cooling	Electricity
Temperature (°C)	60	30–35	18–23	
Demand covered with the PV-T thermal output (kWh/year)	1727	89	921	–
Average rev-HP COP	2.57	3.94	2.51	–
Electricity consumption (kWh/year)	244	2435	3189	12,838

$$\eta_e = 0.188\left(1 - 0.0037\left(T_{PV} - T_{ref}\right)\right) \quad (2)$$

where G" (W/m^2) is the net solar irradiance on the tilted surface, T_{fm} is the mean fluid temperature, T_a is the ambient temperature, u is the wind speed [76], T_{PV} is the PV cell temperature, and T_{ref} is 25 °C (given by the manufacturer). The PV-T collectors are connected in parallel, and therefore, their flow rates and inlet and outlet water temperatures are the same. The collector flow-rate is 50 l/(h·m^2) [77,78]. The PV-T collectors are installed on the industrial building roof facing South (see Fig. 3).

The system has two parallel water storage tanks [79], a 350-litre one for DHW provision and a 263-litre inertia tank which provides space heating or cooling depending on the season (see Fig. 4). In the DHW tank, hot water is supplied from the top of the tank, and water is refilled with mains water from the bottom. An immersed heat exchanger connected to the PV-T collector array runs from the middle to the bottom of the tank, and another one connected with the rev-HP runs in the upper part to heat the water inside the tank up to the DHW set-point temperature (see Fig. 2).

The inertia tank has an immersed heat exchanger connected with the PV-T collector array in the lower part, while water from the rev-HP directly enters the tank from the top and leaves at a medium height to heat/cool the water inside the tank to the set-point temperature for space heating/cooling, depending on the operating mode. The space heating/cooling circuit runs from the bottom to the top of the inertia tank (see Fig. 2). In summer, the PV-T collector array is used at night to cool the inertia tank (radiative cooling), thus reducing the rev-HP consumption.

The rev-HP acts as an auxiliary heating/cooling device. The rev-HP (Yutaki S6) from Hitachi, has a nominal thermal power and COP of 16 kW and 4.57 for heating and 10.5 kW and 3.31 for cooling [80]. With the proposed rev-HP, space heating is provided at 30–35 °C and space cooling at 18–23 °C, through fan-coils (see Table 3). The external unit of the rev-HP is installed on the roof of the industrial building (see Fig. 3 right) and the internal unit on the first floor, besides the storage tanks (see Fig. 4).

The selected a-w rev-HP is more efficient than the previous a-a rev-HP (see Table 3). Furthermore, part of the thermal demand is covered with the PV-T thermal output, so the total electricity consumption of the building is lower in this case, 18,706 kWh/year (see Table 3).

2.2. *Life cycle assessment*

This analysis aims to compare, from an environmental point of view, the proposed S-CCHP system with other conventional alternatives (e.g., a grid-based system and a PV-system). Therefore, the functional unit is a "*building energy system*" able to provide the energy demand of the building, including DHW, space heating, space cooling, and electricity, as detailed in Section 2.1. The proposed system configurations are located in Zaragoza (Spain), and a system lifetime of 20 years has been considered [49,50,58].

As for the LCA boundaries (see Fig. 5), they exclude those subsystems which are common to all the configurations. The most salient example of a common subsystem is the heating/cooling delivery units (fan-coils). Similar to previous studies [57], electronic components such as controls and sensors are not considered, as only the necessary components for the

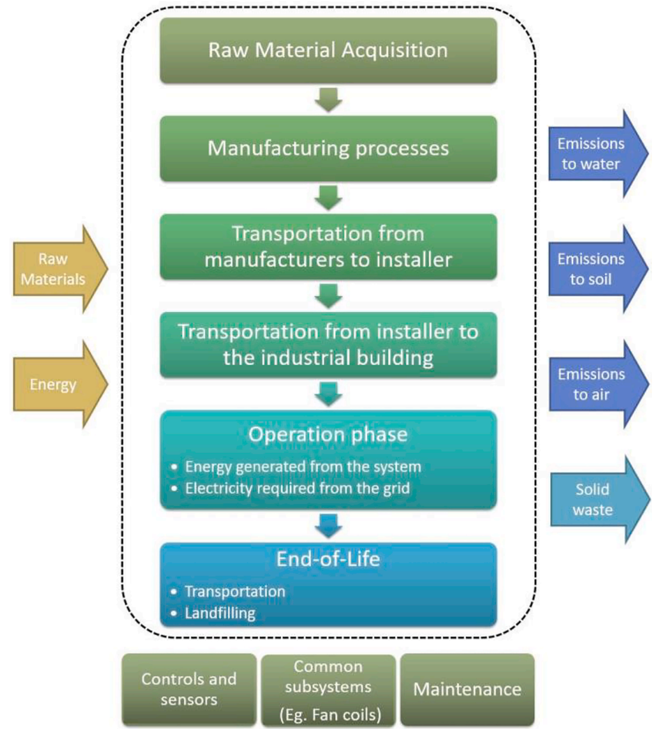

Fig. 5. Life cycle assessment boundaries.

Table 4
EcoInvent dataset selection for the main components and materials used in this study.

Component	EcoInvent
Photovoltaic panel	Photovoltaic panel, single-Si wafer {RoW}| production
Solar collector	Flat plate solar collector, Cu absorber {RoW}| production
Heat pump	Heat pump, brine-water, 10 kW {RoW}| production
Water tanks	Hot water tank, 600 l {RoW}| production
Inverter	Inverter, 2.5 kW {RoW}| production
Pump	Pump, 40 W {RoW}| production
Expansion vessel	Expansion vessel, 25 l {RoW}| production
Propylene glycol	Propylene glycol, liquid {RoW}| market for
Water	Tap water {Europe without Switzerland}| market for
PP	Polypropylene, granulate {RoW}| production
PE	Polyethylene, high density, granulate {RoW}| production
Pipe insulation	Tube insulation, elastomer {RoW}| production

Table 5
Main components considered in the LCI in the three system configurations.

Grid-based system		PV-system		S-CCHP system	
component	kg	component	kg	component	kg
a-a rev-HP	868.4	a-a rev-HP	868.4	new a-w rev-HP	208.0
		PV panels	312.0	PV-T collectors	929.4
		inverter	19.9	inverter	19.9
				storage tanks	486.0
				water pumps	17.8
				expansion vessels	12.0
				propylene glycol	14.8
				water	323.8
				PP pipes	25.2
				PE-Al pipes	17.6
				pipe insulation	2.4

Table 6
Main materials for the PV panel and PV-T collector (values provided per panel/collector).

Main materials	PV panel		PV-T Collector	
Mono-Si PV cells	1.19	Kg	1.19	kg
Aluminium alloy	2.63	Kg	7.34	kg
Solar glass	13.65	Kg	13.65	kg
EVA foil	1.70	Kg	1.70	kg
Copper			2.21	kg
Expanded polystyrene			1.33	kg
Synthetic rubber			1.24	kg
Water, completely softened			0.71	kg
Propylene glycol			0.24	kg
Polyvinylfluoride, film			0.19	kg
Silicone product	0.21	Kg	0.31	kg
Polyethylene terephthalate	0.63	Kg	0.63	kg
Glass fibre reinforced plastic, polyamide	0.32	Kg	0.32	kg
SUBTOTAL PANEL	**20.33**	**Kg**	**31.07**	**kg**
Corrugated board box	1.86	Kg	6.26	kg
Tap water	36.18	Kg	52.16	kg

Table 7
Main materials for the inverter.

Materials	Inverter	
Aluminium alloy	1.30	kg
Copper	5.13	kg
Steel	9.12	kg
Electronic boards and components	1.68	kg
Packaging	2.32	kg
Polymers	0.35	kg
Total	**19.9**	**kg**

Table 8
Main materials for the storage tanks (total amounts for both storage tanks).

Materials	Storage Tanks	
Steel alloys	446.30	kg
Glass wool mat	34.33	kg
PVC	3.43	kg
Paint	1.72	kg
Others	0.22	kg
Total	**486**	**kg**

Table 9
Main materials for the new a-w rev-HP.

Materials	a-w rev-HP	
Steel alloys	148.8	kg
Copper	34.5	kg
Elastomere	15.7	kg
PVC	1.6	kg
Others	7.4	kg
Total	**208**	**kg**

typical operation of the analysed systems are considered within the boundaries. Maintenance and water cleaning for the PV-T collectors are neglected due to their low environmental impact compared to the rest of the impacts during the operation phase.

A Life Cycle Inventory (LCI) is performed for each of the three system configurations, with a "*from cradle to grave*" scope, including raw materials, manufacturing processes, transportation and disposal phases. The included components are shown in detail in Section 3.1. Regarding the *End of Life* phase, although there are valuable materials in the system, a conservative approach has been taken, viz that the system will be sent to a landfill after the use phase [57].

The LCA is calculated following two methodologies: the ReCiPe 2016 Endpoint (H/A) World (2010) v1.03, and the IPCC 2013 GWP, with a time horizon of 100 years. The ReCiPe methodology combines midpoint and endpoint methods, allowing for easier interpretations and comparisons among systems [72,81], and covers a wide range of environmental impact categories such as global warming, fine particulate matter formation, human carcinogenic and non-carcinogenic toxicity, and fossil resources scarcity. The selected (H/A) World (2010) ReCiPe version is the default method and uses a Hierarchist perspective, the Average weighting set, and global normalization factors for the reference year 2010. This version is the one recommended and considered as default by the authors of the methodology [82]. On the other hand, the carbon footprint IPCC 2013 methodology is selected due to the social relevance of global warming [83,84].

The LCI is based on primary data, using the EcoInvent v3.5 database, which is included in the SimaPro v9.0.0.49 software [72]. EcoInvent, developed by the Swiss Centre for Life Cycle Inventories, is one of the most well-known LCI databases. Assignment between the inventory data and EcoInvent datasets is performed following Ecoinvent Guidelines

Table 10
Main components transportation distances from manufacturers to installer.

Component	Transportation	Distance	
PV panels	Freight ship + Truck	16,500 + 300	Km
Collector	Truck	20	Km
Heat Pump	Truck	283	Km
Inverter	Truck	1892	Km
Storage Tanks	Truck	20	Km
Other components	Truck	300	Km

Table 11
Annual solar irradiance in the four selected climates.

Climate	Location	Annual solar irradiance (kWh/year)
Mediterranean	Athens (Greece)	47,601
Continental	Oslo (Norway)	20,871
Oceanic	Paris (France)	31,893
Cold semi-arid	Zaragoza (Spain)	48,607

Table 12
Building electricity consumption in the different system configurations and electricity generated by the solar systems in the four selected climates.

Climate	Building electricity consumption (kWh/year)			Electricity generated (kWh/year)	
	grid-based system	PV-system	S-CCHP system	PV-system	S-CCHP system
Cold semi-arid	23,745	23,745	18,706	8876	8352
Continental	23,745	23,745	17,765	4168	3620
Mediterranean	23,745	23,745	17,663	8635	7474
Oceanic	23,745	23,745	17,837	5961	5171

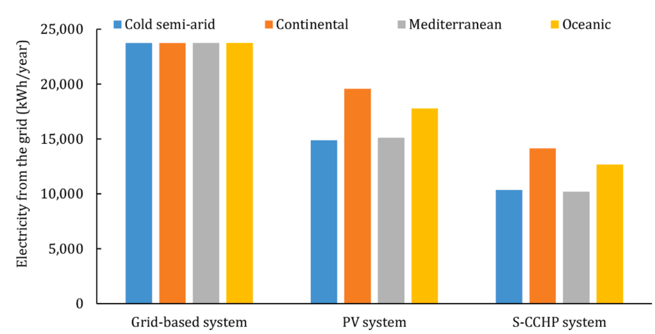

Fig. 6. Electricity imported from the grid in the different system configurations for the four selected locations.

[73]. Table 4 shows the EcoInvent datasets used in this study for the most relevant components. LCI data from the manufacturers are used to properly assess the PV panels and the PV-T collectors and therefore, the dataset of the PV panel is modified according to the manufacturer data. The PV-T collector is implemented as a combination of the modified PV panel and solar thermal collector datasets, according to the manufacturer data [68] (see Section 3.1). The most relevant EcoInvent v3.5 datasets are based on previous EcoInvent reports related to Photovoltaics (for datasets regarding PV panels and inverter) [85], to solar thermal collectors (for solar thermal collectors, water pumps, hot water tanks and expansion vessels datasets) [86] and to heat pumps [87]. For standard components, Ecoinvent datasets have been used. It should be noted that the same heat pump dataset is used for both types of heat pumps, as the examples found in EcoInvent for an air-to-air rev-HP use also the dataset shown in Table 4, adjusting the dataset to the nominal power of the specific case.

3. Results and discussion

First, a summary of the main LCI results is presented (Section 3.1), followed by the main results of the energy balance during the operation phase (Section 3.2). Then, the LCA results of the three system configurations are presented and compared, as well as the main findings of the sensitivity analyses (Section 3.3).

3.1. Life cycle inventory

Following the LCA methodology [70,71], an LCI is conducted to evaluate the energy and emission loads associated with the different system components in each analysed system configuration. EcoInvent v3.5 database is used for the off-the-shelf components (e.g. inverter, storage tanks, pipes, water pumps), while data for the PV panels and the hybrid PV-T collectors were provided by the manufacturer [68].

The main components of the proposed S-CCHP system are: the PV-T collectors, two water storage tanks, water pumps, expansion vessels, an inverter and the new a-w rev-HP. Piping, as well as the circulating fluid, are considered in the LCI. In the grid-based system, the current a-a rev-HP is considered, and in the PV-system, the main components are the PV panels, an inverter and the current a-a rev-HP (see Table 5).

The primary materials of a PV panel are silicon wafers for the PV cells, solar glass, aluminium alloy, ethylvinylacetate (EVA) and polyethylene. The PV-T collector has also copper for the thermal absorber, expanded polystyrene for the thermal insulation, and the fluid (a mixture of water and propylene glycol in this case) (see Table 6). The LCI also considers other materials used to manufacture, transport, and install the components, such as corrugated board boxes and tap water.

The main materials of the inverter, storage tanks and the new a-w rev-HP are shown in Tables 7, 8 and 9. Steel is the primary material used in all the components.

The supply chain of the different components from their manufacturers' site to the installer site, located in Zaragoza (Spain), has been considered (see Table 10). Transportations by truck have been calculated with the "*Transport, freight, lorry >32 metric ton, euro6 {RER}*" dataset, and by ship with "*Transport, freight, sea, transoceanic ship {GLO}*". The transportation from the installer site to the industrial building is also considered (estimated as 50 Km by "*Transport, freight, lorry 16–32 metric ton, euro5 {RER}*"). Finally, the transportation from the installation site to the landfill has also been taken into account (estimated as 30 Km by "*Transport, freight, lorry 16–32 metric ton, euro5 {RER}*").

3.2. Energy balance during the operation phase

The LCA methodology considers raw materials, manufacturing processes, transportation, operation and end of life phases for each system component. This section details the energy balance during the operation phase, as it generates most of the overall environmental impacts. The energy balance for the operation phase includes the annual electricity consumption of the building in each system configuration (see Section 2.1), as well as the electricity generated by the analysed solar systems. It should be noted that the effect of degradation throughout the system lifetime in the system performance has not been considered. The performance degradation is expected to occur mainly in the PV encapsulate, both in the PV-system and in the S-CCHP system. However, this degradation is very low. Recent research [88] showed that multi-crystalline silicon PV modules (such as those proposed in this study) have an average annual degradation rate of 0.18% under outdoor conditions, which would involve slightly lower electricity generation of the solar systems throughout the years, and thus a marginally more significant amount of electricity imported from the grid with time in the case of the solar systems.

Four alternative climates are selected to analyse the effect of the weather conditions on the solar systems' performance. Table 11 shows the annual solar irradiance in the four selected climates corresponding to four different geographical locations within Europe.

As shown in Table 12, the electricity generated by the PV-system and the proposed S-CCHP system varies considerably with the climate. The PV-system generates twice as much electricity in locations with high annual solar irradiance (see the Mediterranean and Cold semi-arid climates in Table 11) compared with locations with low solar irradiance (see the Continental climate in Table 11), and the S-CCHP system even more (2.3 times more).

As detailed in Section 2.1, the grid-based system and the PV-system consider the a-a rev-HP and electrical heater previously installed in the industrial building to provide the DHW, heating and cooling demands. Therefore, the building electricity consumption provided by the

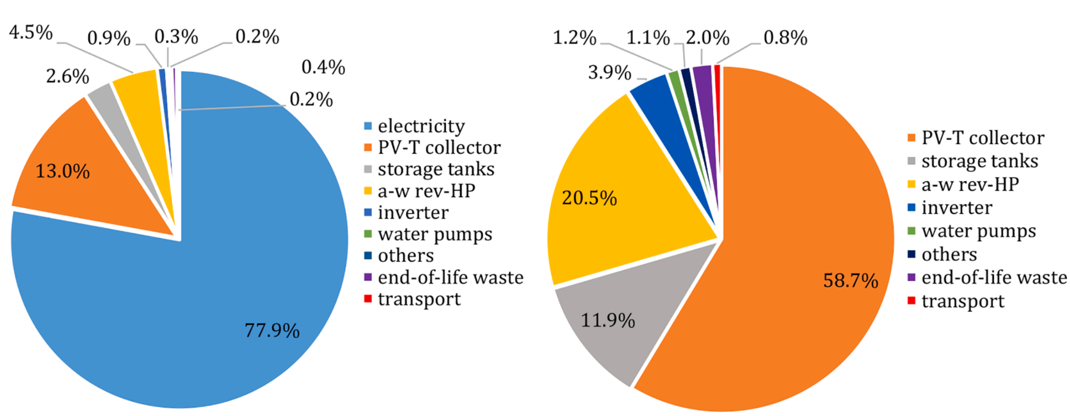

Fig. 7. Share of the S-CCHP system components in the total environmental impact, including grid electricity consumption (left) and (right) not including the operation phase. (ReCiPe 2016 Endpoint (H/A), Zaragoza location, 20 years lifetime.)

Table 13

Environmental impact in the 22 impact categories according to the ReCiPe 2016 Endpoint (H/A) method and according to the IPCC GWP 100a method for the different S-CCHP system components (Zaragoza location, 20 years lifetime).

Impact category		Total	electricity	PV-T collector	storage tanks	a-w rev-HP	Inverter	water pumps	others	end-of-life waste	transport
IPCC GWP 100a (kg $CO_{2\ eq}$)		82,360	68,076	9,077	1,401	2,506	254	71	237	619	120
ReCiPe 2016 Endpoint (kPt)	Fine particulate matter formation	2.105	1.738	0.243	0.038	0.056	0.012	0.004	0.004	0.004	0.005
	Global warming, Human health	1.309	1.078	0.145	0.022	0.044	0.004	0.001	0.004	0.010	0.002
	Human non-carcinogenic toxicity	0.445	0.216	0.114	0.013	0.077	0.018	0.004	0.001	0.003	$1.31\cdot10^{-04}$
	Human carcinogenic toxicity	0.294	0.189	0.041	0.040	0.016	0.003	0.002	0.001	0.002	$1.37\cdot10^{-04}$
	Global warming, Terrestrial ecosystems	0.131	0.108	0.014	0.002	0.004	$4.06\cdot10^{-04}$	$1.12\cdot10^{-04}$	$3.79\cdot10^{-04}$	$9.73\cdot10^{-04}$	$1.88\cdot10^{-04}$
	Terrestrial acidification	0.059	0.051	0.005	$6.07\cdot10^{-04}$	$1.64\cdot10^{-03}$	$3.36\cdot10^{-04}$	$9.68\cdot10^{-05}$	$9.41\cdot10^{05}$	$7.81\cdot10^{-05}$	$1.77\cdot10^{04}$
	Fossil resource scarcity	0.037	0.031	0.004	$5.16\cdot10^{-04}$	$6.06\cdot10^{-04}$	$1.24\cdot10^{-04}$	$3.09\cdot10^{-05}$	$2.94\cdot10^{-04}$	$9.47\cdot10^{-05}$	$1.18\cdot10^{-04}$
	Water consumption, Human health	0.031	0.024	0.006	$4.17\cdot10^{-04}$	$3.75\cdot10^{-04}$	$7.72\cdot10^{-05}$	$1.92\cdot10^{-05}$	$1.23\cdot10^{-04}$	$5.30\cdot10^{-05}$	$1.02\cdot10^{-05}$
	Ozone formation, Terrestrial ecosystems	0.019	0.016	0.002	$2.74\cdot10^{-04}$	$2.60\cdot10^{-04}$	$6.95\cdot10^{-05}$	$1.80\cdot10^{-05}$	$4.16\cdot10^{-05}$	$4.48\cdot10^{-05}$	$8.62\cdot10^{-05}$
	Freshwater eutrophication	0.016	0.011	0.003	$3.38\cdot10^{-04}$	$1.21\cdot10^{-03}$	$2.95\cdot10^{-04}$	$6.47\cdot10^{-05}$	$2.81\cdot10^{-05}$	$2.97\cdot10^{-05}$	$5.34\cdot10^{-06}$
	Land use	0.015	0.013	0.001	$3.91\cdot10^{-04}$	$1.93\cdot10^{-04}$	$6.22\cdot10^{-05}$	$1.62\cdot10^{-05}$	$2.77\cdot10^{-05}$	$4.34\cdot10^{-05}$	$1.38\cdot10^{-05}$
	Ionizing radiation	0.007	0.006	0.000	$9.93\cdot10^{-06}$	$1.70\cdot10^{-05}$	$4.77\cdot10^{-06}$	$9.18\cdot10^{-07}$	$1.76\cdot10^{-06}$	$1.94\cdot10^{-06}$	$5.96\cdot10^{-07}$
	Water consumption, Terrestrial ecosystem	0.005	0.003	0.001	$8.46\cdot10^{-05}$	$7.69\cdot10^{-05}$	$1.60\cdot10^{-05}$	$3.95\cdot10^{-06}$	$2.49\cdot10^{-05}$	$1.08\cdot10^{-05}$	$2.06\cdot10^{-06}$
	Ozone formation, Human health	0.004	0.003	$3.57\cdot10^{-04}$	$5.64\cdot10^{-05}$	$5.34\cdot10^{-05}$	$1.42\cdot10^{-05}$	$3.73\cdot10^{-06}$	$8.36\cdot10^{-06}$	$9.42\cdot10^{-06}$	$1.82\cdot10^{-05}$
	Freshwater ecotoxicity	0.003	0.003	$3.25\cdot10^{-04}$	$4.70\cdot10^{-05}$	$2.14\cdot10^{-04}$	$5.09\cdot10^{-05}$	$1.17\cdot10^{-05}$	$2.41\cdot10^{-06}$	$1.26\cdot10^{-04}$	$4.02\cdot10^{-07}$
	Terrestrial ecotoxicity	0.003	0.001	$1.41\cdot10^{-03}$	$7.45\cdot10^{-05}$	$4.75\cdot10^{-04}$	$9.37\cdot10^{-05}$	$2.91\cdot10^{-05}$	$2.77\cdot10^{-06}$	$1.46\cdot10^{-05}$	$4.70\cdot10^{-06}$
	Mineral resource scarcity	0.001	$3.28\cdot10^{-04}$	$1.61\cdot10^{-04}$	$1.17\cdot10^{-04}$	$9.10\cdot10^{-05}$	$2.08\cdot10^{-05}$	$1.01\cdot10^{-05}$	$2.10\cdot10^{-06}$	$1.30\cdot10^{-06}$	$2.70\cdot10^{-07}$
	Marine ecotoxicity	0.001	$4.84\cdot10^{-04}$	$7.49\cdot10^{-05}$	$1.01\cdot10^{-05}$	$4.70\cdot10^{-05}$	$1.13\cdot10^{-05}$	$2.58\cdot10^{-06}$	$5.13\cdot10^{-07}$	$2.31\cdot10^{-05}$	$1.06\cdot10^{-07}$
	Stratospheric ozone depletion	$4.36\cdot10^{-04}$	$3.45\cdot10^{-04}$	$4.27\cdot10^{-05}$	$4.06\cdot10^{-06}$	$3.68\cdot10^{-05}$	$1.91\cdot10^{-06}$	$4.18\cdot10^{-07}$	$7.84\cdot10^{-07}$	$3.48\cdot10^{-06}$	$5.84\cdot10^{-07}$
	Marine eutrophication	$3.59\cdot10^{-06}$	$2.57\cdot10^{-06}$	$7.12\cdot10^{-07}$	$4.66\cdot10^{-08}$	$1.94\cdot10^{-07}$	$4.11\cdot10^{-08}$	$1.01\cdot10^{-08}$	$6.31\cdot10^{-09}$	$1.06\cdot10^{-08}$	$9.73\cdot10^{-10}$
	Global warming, Freshwater ecosystems	$3.58\cdot10^{-06}$	$2.95\cdot10^{-06}$	$3.95\cdot10^{-07}$	$6.07\cdot10^{-08}$	$1.20\cdot10^{-07}$	$1.11\cdot10^{-08}$	$3.07\cdot10^{-09}$	$1.04\cdot10^{-08}$	$2.66\cdot10^{-08}$	$5.14\cdot10^{-09}$
	Water consumption, Aquatic ecosystems	$3.28\cdot10^{-07}$	$2.54\cdot10^{-07}$	$6.10\cdot10^{-08}$	$4.86\cdot10^{-09}$	$4.60\cdot10^{-09}$	$1.04\cdot10^{-09}$	$2.52\cdot10^{-10}$	$1.25\cdot10^{-09}$	$6.08\cdot10^{-10}$	$1.17\cdot10^{-10}$
	Total	**4.485**	**3.493**	**0.582**	**0.118**	**0.203**	**0.039**	**0.012**	**0.011**	**0.020**	**0.008**

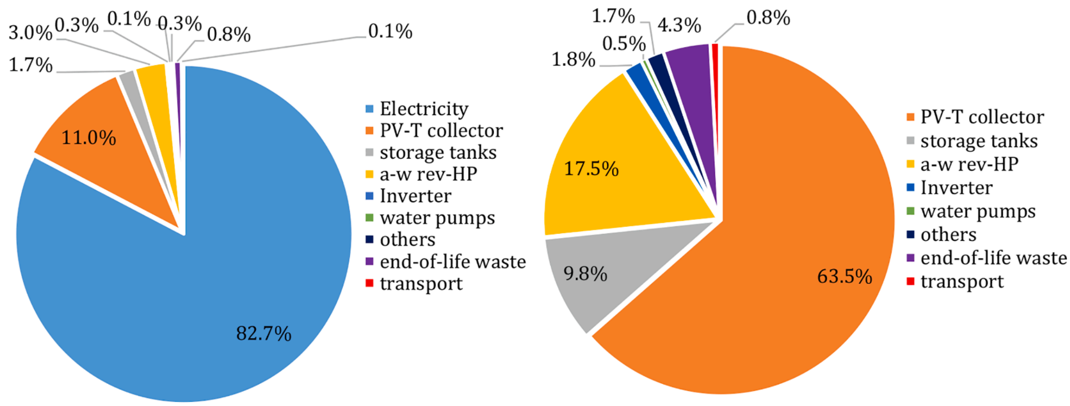

Fig. 8. Share of the S-CCHP system components in the total environmental impact, including grid electricity consumption (left) and (right) not including the use phase. (IPCC GWP 100a method, Zaragoza location and 20 years lifetime.)

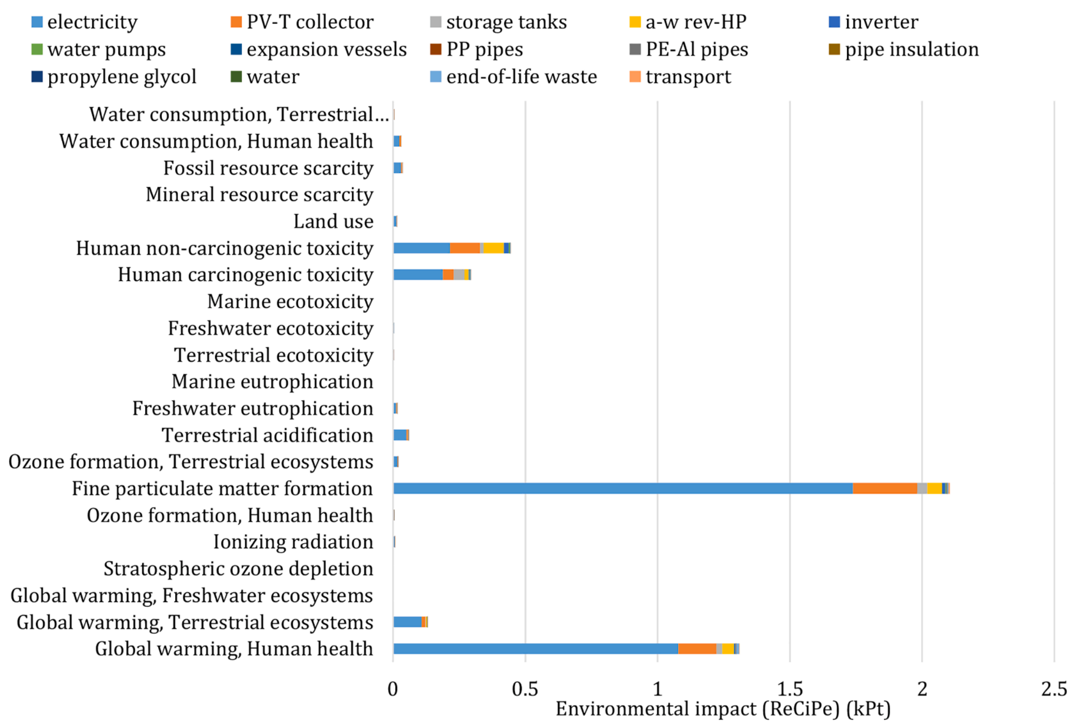

Fig. 9. Share of the different S-CCHP system components in the 22 environmental impact categories. (ReCiPe 2016 Endpoint (H/A) method, Zaragoza location, 20 years lifetime).

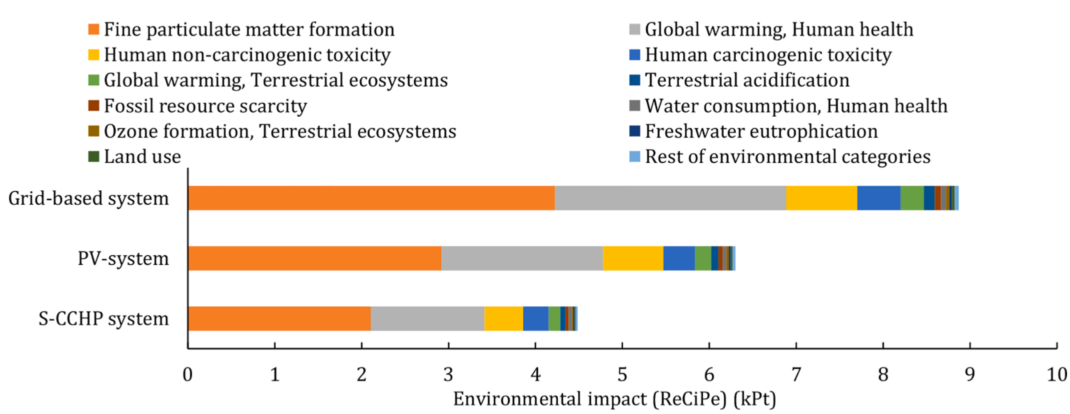

Fig. 10. Environmental impact in the 11 more relevant impact categories according to the ReCiPe 2016 Endpoint (H/A) method for the three system configurations in Zaragoza (Spain). Legend entries are sorted in the order of decreasing importance, and minor categories are grouped under a "rest of environmental categories" heading.

Table 14
Environmental impact in the 22 impact categories according to the ReCiPe 2016 Endpoint (H/A) method and the IPCC GWP 100a method for the three system configurations in Zaragoza (Spain).

Impact category		Grid-based system	PV-system	S-CCHP system
IPCC GWP 100a (tons $CO_{2\ eq}$)		166.9	116.3	82.4
ReCiPe 2016 Endpoint (kPt)	Fine particulate matter formation	4.223	2.918	2.105
	Global warming, Human health	2.661	1.860	1.309
	Human non-carcinogenic toxicity	0.819	0.692	0.445
	Human carcinogenic toxicity	0.501	0.365	0.294
	Global warming, Terrestrial ecosystems	0.266	0.186	0.131
	Terrestrial acidification	0.123	0.083	0.059
	Fossil resource scarcity	0.074	0.051	0.037
	Water consumption, Human health	0.057	0.042	0.031
	Ozone formation, Terrestrial ecosystems	0.039	0.026	0.019
	Freshwater eutrophication	0.031	0.023	0.016
	Land use	0.030	0.020	0.015
	Ionizing radiation	0.015	0.009	0.007
	Water consumption, Terrestrial ecosystem	0.008	0.006	0.005
	Ozone formation, Human health	0.008	0.006	0.004
	Freshwater ecotoxicity	0.007	0.005	0.003
	Terrestrial ecotoxicity	0.005	0.005	0.003
	Mineral resource scarcity	$1.13{\cdot}10^{-03}$	$9.31{\cdot}10^{-04}$	$7.32{\cdot}10^{-04}$
	Marine ecotoxicity	$1.32{\cdot}10^{-03}$	$9.46{\cdot}10^{-04}$	$6.53{\cdot}10^{-04}$
	Stratospheric ozone depletion	$9.47{\cdot}10^{-04}$	$6.87{\cdot}10^{-04}$	$4.36{\cdot}10^{-04}$
	Marine eutrophication	$6.70{\cdot}10^{-06}$	$5.03{\cdot}10^{-06}$	$3.59{\cdot}10^{-06}$
	Global warming, Freshwater ecosystems	$7.27{\cdot}10^{-06}$	$5.08{\cdot}10^{-06}$	$3.58{\cdot}10^{-06}$
	Water consumption, Aquatic ecosystems	$6.02{\cdot}10^{-07}$	$4.40{\cdot}10^{-07}$	$3.28{\cdot}10^{-07}$
	Total	**8.869**	**6.299**	**4.485**

building manager is considered in these configurations (23,745 kWh, see Section 2.1).

Meanwhile, as detailed in Section 2.1.4, the proposed S-CCHP system includes a more efficient a-w rev-HP, and part of the thermal demand is covered with the PV-T thermal output, so the total electricity consumption of the building in this configuration is lower. The efficiencies of the PV-T collectors and the a-w rev-HP depend on the weather conditions, so, in this configuration, the final building energy consumption varies with the climate (see Table 12). To obtain these values, the transient model of the S-CCHP system is run with a 15-min time-step for one year in the four locations detailed in Table 11.

Fig. 6 shows that the electricity imported from the grid varies depending on the climate and the system configuration, being considerably lower in the proposed S-CCHP system, between 40% and 57% lower than in the grid-based system, depending on the climate. Also, in all cases, the electricity imported from the grid is lower in the S-CCHP system than in the PV-system, which is expected to considerably influence the LCA results.

3.3. Life cycle assessment results

First, the LCA results of the proposed S-CCHP system in the current location (Zaragoza, Spain) are analysed in detail, assuming a system lifetime of 20 years [20]. Then, the results are compared with the two alternative configurations: the grid-based system and a conventional PV-system (Section 3.3.1). This stage is followed by the assessment of the influence of the system lifetime on the LCA results for the three system configurations, grid-based system, PV-system and S-CCHP system in the current location (Section 3.3.2). Later on, the LCA is performed in four alternative climates for the three system configurations, assuming a system lifetime of 20 years (Section 3.3.3). Finally, the influence of the power generation mix on the LCA results is assessed for the three system configurations, considering the current climate and assuming a system lifetime of 20 years (Section 3.3.4).

3.3.1. Assessment of system configurations

Fig. 7 left shows the share of the S-CCHP system components in the total environmental impact, according to the ReCiPe 2016 Endpoint (H/A) method, when the S-CCHP system is installed in the analysed building in Zaragoza (Spain), and assuming a system lifetime of 20 years [20]. It is observed that electricity accounts for 77.9% of the total environmental impact, with 3.49 kPts out of the total 4.48 kPts (see Table 13), followed by the PV-T collectors with 0.58 kPts (13%).

When electricity is not considered, the PV-T collectors account for 58.7% of the total share, the a-w rev-HP for 20.5% and the storage tanks for 11.9% (see Fig. 7 right). The silicon PV cells have the highest environmental impact within the PV-T collector, in line with previous studies [57], followed by the copper thermal absorber.

Similar results are obtained with the IPCC GWP 100a method. Fig. 8 left shows that electricity accounts for 82.7% of the total $CO_{2eq.}$ emissions (68,076 kg $CO_{2eq.}$ of the total 82,360 kg $CO_{2eq.}$, see Table 13), followed by the PV-T collectors with 9,077 kg $CO_{2eq.}$ (11.0%). When grid electricity consumption is not included, the PV-T collectors account for 63.6% of the total share, the a-w rev-HP for 17.5% and the storage tanks for 9.8% (see Fig. 8 right).

In terms of impact categories, fine particulate matter formation is the most relevant one, contributing with 46.9% of the total share (2.11 kPts out of the total 4.48 kPts, see Table 13), followed by global warming (damage to human health, 1.31 kPts, 29.2%), human non-carcinogenic toxicity (0.44 kPts, 9.9%) and human carcinogenic toxicity (0.29 kPts, 6.6%). The rest of the environmental impact categories account for less than 3% of the total share (see Fig. 9).

The results show that the proposed S-CCHP system has half (49%) of the environmental impact of the grid-based system, according to the ReCiPe 2016 Endpoint (H/A) method (4.48 kPts *vs* 8.87 kPts respectively, see Fig. 10 and Table 14). Meanwhile, the PV-system has 29% less environmental impact than the grid-based system (6.30 kPts). This is attributed mainly to the operation phase of the analysed configurations. As shown in Figs. 7 and 9, most environmental impacts are due to grid electricity, so the configurations with less electricity imported from the grid (see Fig. 6) have lower environmental impacts.

Similar results are obtained following the IPCC GWP 100a method. Table 14 shows that the proposed S-CCHP system has 51% fewer $CO_{2\ eq.}$

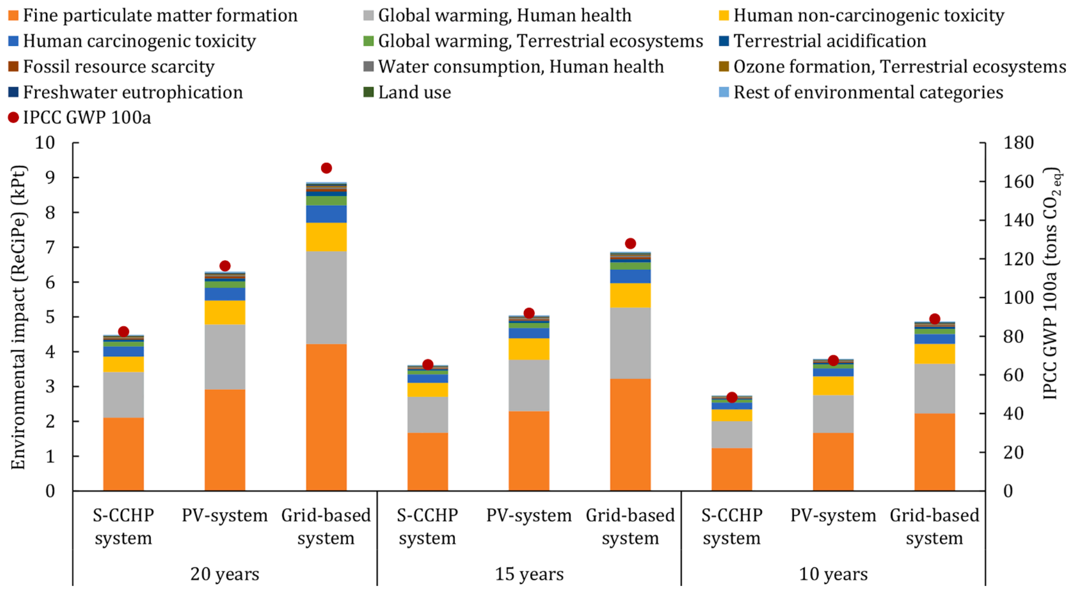

Fig. 11. (Left axis) Environmental impact in the 11 more relevant impact categories according to the ReCiPe 2016 Endpoint (H/A) method and (right axis) according to the IPCC GWP 100a method, for the three system configurations with three system lifetimes (10, 15 and 20 years) in Zaragoza (Spain).

Table 15
Total environmental impact according to the ReCiPe 2016 Endpoint (H/A) and the IPCC GWP 100a methods for the three system configurations with the three system lifetimes (10, 15 and 20 years) in Zaragoza (Spain).

System lifetime		IPCC GWP 100a		ReCiPe	
		tons CO_2 eq	% reduction	kPt	% reduction
10 years	**Grid-based system**	88.6	–	4.864	–
	PV-system	67.5	24%	3.791	22%
	S-CCHP system	48.3	46%	2.739	44%
15 years	**Grid-based system**	127.6	–	6.867	–
	PV-system	91.9	28%	5.045	27%
	S-CCHP system	65.3	49%	3.612	47%
20 years	**Grid-based system**	166.9	–	8.869	–
	PV-system	116.3	30%	6.299	29%
	S-CCHP system	82.4	51%	4.485	49%

emissions than the grid-based system (82.4 tons of $CO_{2\ eq.}$ *vs* 166.9 tons of $CO_{2\ eq.}$), while the PV-system has 30% fewer $CO_{2\ eq.}$ emissions than the grid-based system (116.3 tons of $CO_{2\ eq.}$). Therefore, it can be concluded that the proposed S-CCHP system appears to be a very promising alternative to reduce the environmental impacts associated with the building energy consumption.

3.3.2. *Influence of the system lifetime*

Three lifetimes are considered in the current location (Zaragoza, Spain), 10, 15 and 20 years [57], for the three system configurations, grid-based system, PV-system and proposed S-CCHP system.

Fig. 11 shows that, as expected, the environmental impacts in all the system configurations increase with the system lifetimes due to the increase in the operation years and thus in the associated electricity imported from the grid.

Table 15 shows the percentage reduction in the environmental impacts of the solar systems compared to the grid-based system for the different system lifetimes. The PV-system attains an LCA reduction of $CO_{2\ eq.}$ emissions of 24% to 30% for 10 to 20 years of system lifetime according to the IPCC GWP 100a method, increasing with the system lifetime. Meanwhile, the proposed S-CCHP system achieves an LCA reduction of $CO_{2\ eq.}$ emissions of 46% to 51% for 10 to 20 years of system lifetime, compared to the grid-based system. Similar results are obtained using the ReCiPe methodology.

It is also observed that the proposed S-CCHP system considering a 10-year lifetime reduces the environmental impacts further than the PV-system assuming a 15-year lifetime (40.5 tons $CO_{2\ eq.}$ emission reduction *vs* 36.0 tons $CO_{2\ eq.}$ emission reduction, and 2.13 kPts reduction *vs* 1.82 kPts reduction, respectively). Similarly, the proposed S-CCHP system considering a 15-year lifetime reduces the environmental impacts more than the PV-system assuming a 20-year lifetime (62.5 tons $CO_{2\ eq.}$ emission reduction *vs* 50.6 tons $CO_{2\ eq.}$ emission reduction, and 3.25 kPts reduction *vs* 2.57 kPts reduction, respectively).

Therefore, it can be concluded that although the proposed S-CCHP system might have a shorter lifetime than the PV-system, for instance, because of the mechanical components required, it would still reduce the environmental impacts of the building energy consumption compared with a PV-system.

Annualising the environmental impacts per operating year, the annual impacts decrease with the system lifetime (see Fig. 12). This reduction is more considerable for the S-CCHP system (15% reduction for 20-years lifetime compared to 10-years lifetime) than for the PV-system (13%) and than for the grid-based system (5%). Again, this is, attributed to the lower amount of electricity imported from the grid in the S-CCHP system, which becomes more significant as the operating years increase.

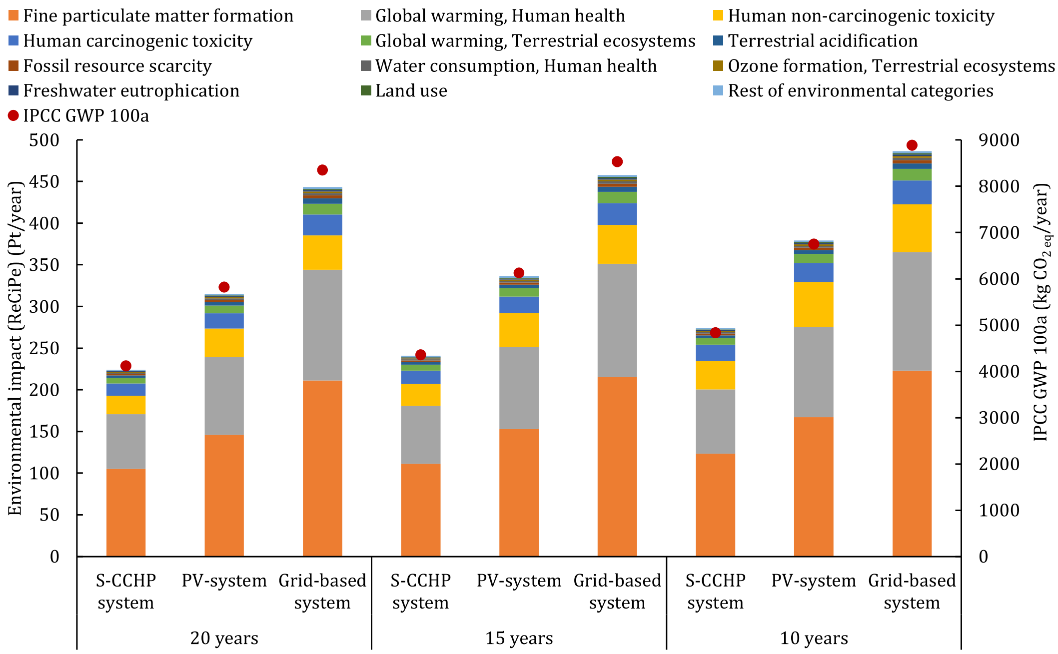

Fig. 12. (Left axis) Environmental impact per operating year in the 11 more relevant impact categories according to the ReCiPe 2016 Endpoint (H/A) method and (right axis) according to the IPCC GWP 100a method, for the three system configurations with three system lifetimes (10, 15 and 20 years) in Zaragoza (Spain).

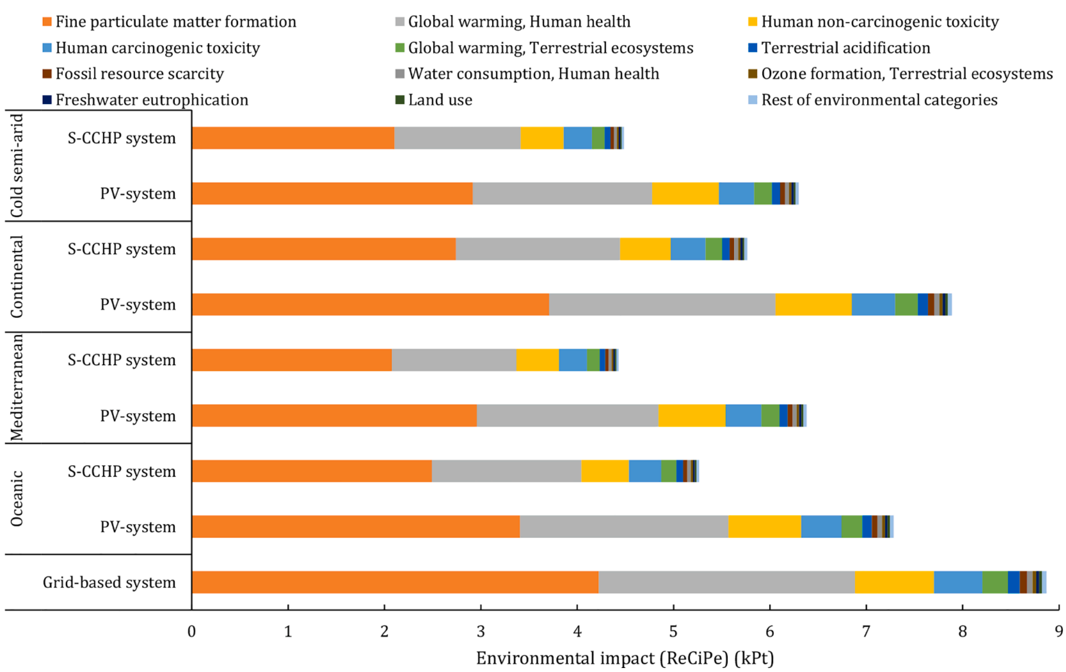

Fig. 13. Environmental impact in the eleven more relevant impact categories according to the ReCiPe 2016 Endpoint (H/A) method for the three system configurations in the four different climates.

3.3.3. *Influence of solar irradiance*

This section analyses the influence of solar irradiance on the LCA results for the three system configurations assuming a 20-year lifetime in the selected climates. As shown in Section 3.2, solar irradiance influences the electricity generated by the solar systems and therefore, it is expected to impact the LCA results of the solar systems. In this analysis, the LCA results of the grid-based system are the same in the different climates, as the electricity that should be imported from the grid is the same (see Table 12 and Fig. 6).

Fig. 13 shows that the scenario with the lowest environmental impact corresponds to the S-CCHP system installed in a Mediterranean climate (4.43 kPts and 81.3 tons $CO_{2\ eq.}$), which coincides with the scenario with the smallest amount of electricity imported from the grid (see Fig. 6). The results show that there is a 27% difference in the environmental impacts (according to the IPCC GWP 100a method) of the PV-system between the most suitable climate (Cold semi-arid) and the least suitable climate (Continental). Similar results (25% difference) are obtained with the ReCiPe 2016 Endpoint (H/A) method. In the case of the S-CCHP system, the differences between the most suitable (Mediterranean) and the least suitable climate (Continental) are 32% and 30%

Table 16
Total environmental impact according to the ReCiPe 2016 Endpoint (H/A) method and according to the IPCC GWP 100a method for the three system configurations in the four analysed climates.

		IPCC GWP 100a		ReCiPe	
		tons $CO_{2\ eq}$	% reduction	kPt	% reduction
	Grid-based system	166.9	–	8.869	–
Oceanic	**PV-system**	135.5	19%	7.283	18%
	S-CCHP system	97.6	42%	5.265	41%
Mediterranean	**PV-system**	117.9	29%	6.381	28%
	S-CCHP system	81.3	51%	4.430	50%
Continental	**PV-system**	147.3	12%	7.887	11%
	S-CCHP system	107.3	36%	5.764	35%
Cold semi-arid	**PV-system**	116.3	30%	6.299	29%
	S-CCHP system	82.4	51%	4.485	49%

according to the IPCC GWP 100a method and the ReCiPe 2016 Endpoint (H/A) method, respectively. All the analysed solar scenarios have lower environmental impacts than the baseline configuration (grid-based system).

Table 16 shows the percentage reduction in the environmental impacts of the solar systems compared to the grid-based system for the different climates. The PV-system attains an LCA reduction of $CO_{2\ eq.}$ emissions of 12% and 30% for the Continental and Cold semi-arid climates, respectively, according to the IPCC GWP 100a method. Intermediate results are obtained in the Oceanic (19%) and Mediterranean (29%) climates. Meanwhile, the proposed S-CCHP system achieves an LCA reduction of $CO_{2\ eq.}$ emissions of 36% and 51% for the Continental and Cold semi-arid/Mediterranean climates, respectively, compared to the grid-based system. Similar results are obtained using the ReCiPe methodology.

3.3.4. *Influence of the power generation mix*

The power generation mix considerably varies from country to country, and it is expected to influence the LCA results. Four electricity mixes are considered, from a highly decarbonised electricity grid to a fossil-fuel predominant grid. This section analyses the LCA results for the three system configurations assuming a 20-year lifetime considering four different power generation mixes, corresponding to four European countries (see Fig. 14).

The shares of the different generation technologies in the country electricity grid are the ones available in the low voltage datasets but modified to calculate with the latest energy mixes available in EcoInvent (from the year 2017) [85]. As shown in Fig. 14, Spain is characterised by a wide power generation mix, with fossil fuels (coal + oil) accounting for 18% of the total energy share, natural gas and cogeneration 12%, nuclear 20% and renewable energies (hydro, solar and wind) 40%. Meanwhile, Greece has a lower share of renewables (31% in total), being predominant in the use of fossil fuels, natural gas and cogeneration (55% in total). France has a considerably different electricity mix, with nuclear accounting for 71% of the total electricity share, and renewables 18% (see Fig. 14). In Norway, 92% of the power generation mix comes from hydropower, and natural gas and cogeneration have a very small share (0.2% combined).

Fig. 15 shows a significant difference in the environmental impacts depending on the power generation mix. The environmental impacts of the system configurations are 2.2–2.4 times higher in Greece than in Spain according to the ReCiPe methodology, and 2.1–2.2 times higher according to the IPCC GWP 100a methodology. The differences are much larger when comparing the results of Greece (fossil-fuel predominant grid) and Norway (highly decarbonised electricity grid), with environmental impacts 6.5–10.4 times larger in Greece than in Norway according to the ReCiPe methodology, and 8.6–15.6 times larger according to the IPCC GWP 100a methodology. This results are attributed to the current power generation mix in both countries, as in Norway

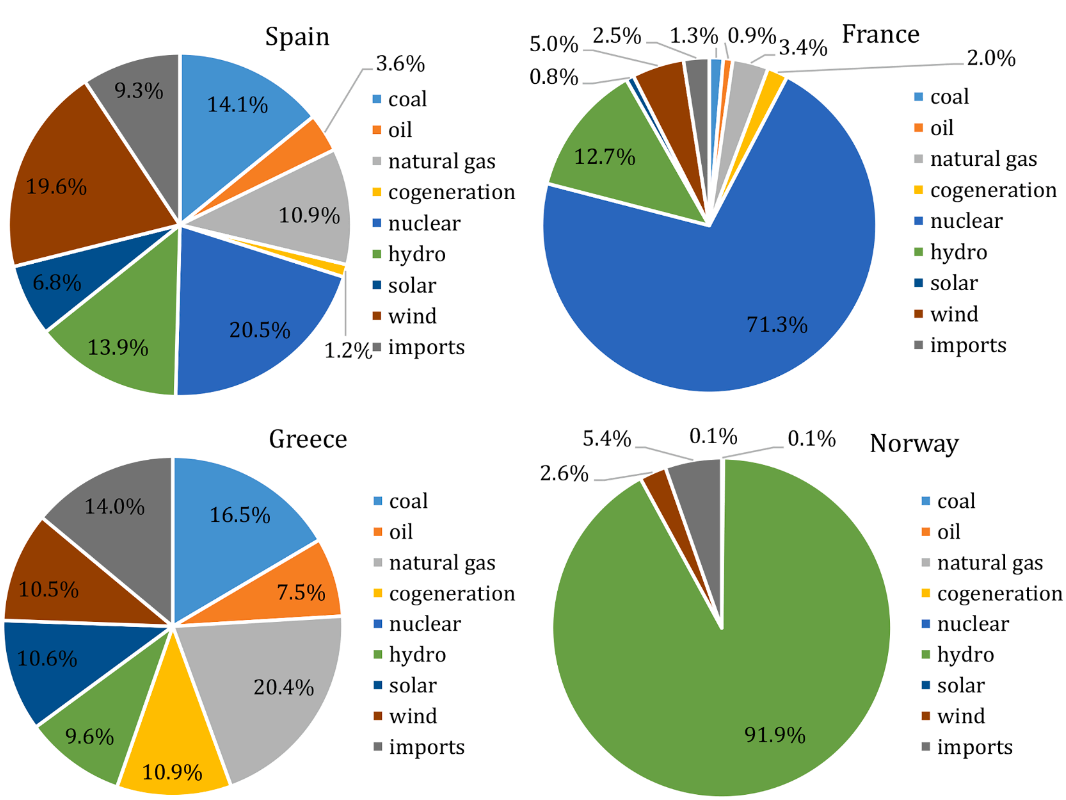

Fig. 14. Power generation mix of the countries selected for the sensitivity analysis.

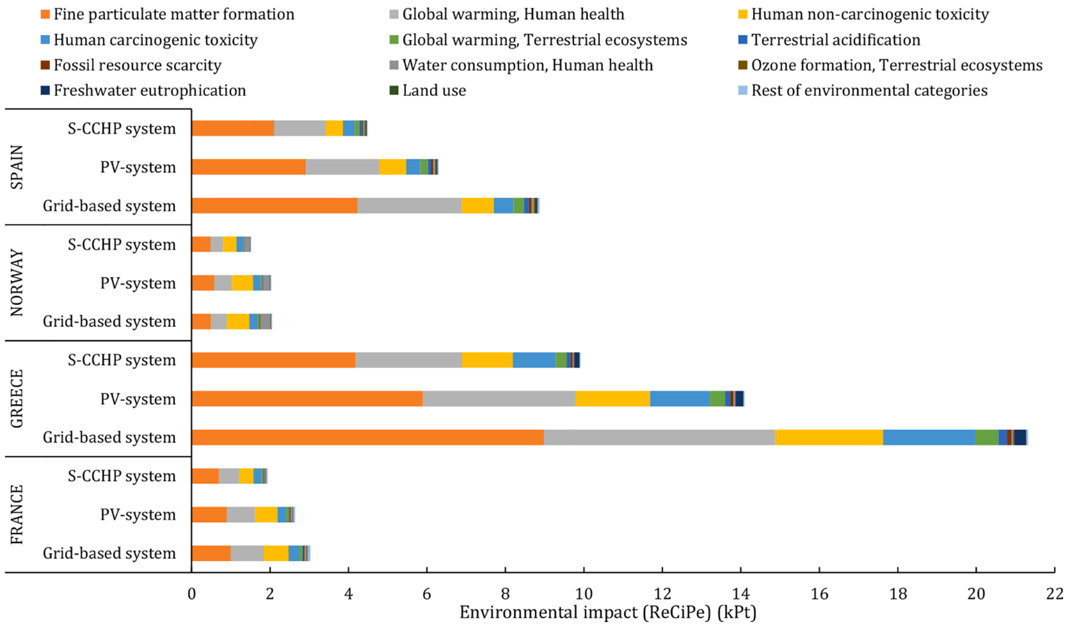

Fig. 15. Environmental impact in the eleven more relevant impact categories according to the ReCiPe 2016 Endpoint (H/A) method for the three system configurations in the four power generation mixes.

Table 17
Total environmental impact according to the ReCiPe 2016 Endpoint (H/A) method and according to the IPCC GWP 100a method for the three system configurations in the four power generation mixes.

	Impact category	IPCC GWP 100a		ReCiPe	
		tons CO_2 eq	% reduction	kPt	% reduction
France	**Grid-based system**	52.3	–	3.026	–
	PV-system	44.6	15%	2.640	13%
	S-CCHP system	32.4	38%	1.937	36%
Greece	**Grid-based system**	372.8	–	21.323	–
	PV-system	245.2	34%	14.098	34%
	S-CCHP system	172.1	54%	9.916	53%
Norway	**Grid-based system**	23.8	–	2.053	–
	PV-system	26.7	-12%	2.031	1%
	S-CCHP system	20.0	16%	1.513	26%
Spain	**Grid-based system**	166.9	–	8.869	–
	PV-system	116.3	30%	6.299	29%
	S-CCHP system	82.4	51%	4.485	49%

92% of the grid electricity comes from hydropower, while in Greece 55% of the grid electricity comes from fossil fuels, natural gas and cogeneration (see Fig. 14). Consequently, the environmental impacts associated with the electricity imported from the grid are considerably larger in Greece than in Norway.

Nevertheless, in the four geographical locations analysed in this study, the S-CCHP system providing the energy needs of an industrial building leads to a reduction of the environmental impacts compared to the grid-based system (see Table 17). This reduction ranges from 16% to 26% (depending on the methodology) in Norway to 53–54% in Greece. France and Spain have intermediate values of 36–38% and 49–51%, respectively.

The results show that implementing a PV-system in Norway resulted in a 12% increase in the environmental impacts according to the IPCC GWP 100a methodology, compared to the grid-based system. According to the ReCiPe methodology, the PV-system has approximately the same environmental impacts as the grid-based system. This means that in this location, due to the highly decarbonised electricity grid, installing a PV-system in this type of industrial building might not be beneficial from an environmental point of view. In the rest of the analysed power generation mixes, the implementation of a PV-system results in a 13–15%, 34% and 29–30% environmental impact reduction compared to the grid-based system in France, Greece and Spain, respectively. Still, this reduction is considerably lower than the potential environmental impact reduction achieved by the proposed S-CCHP system.

4. Further discussion and conclusions

This work presents the main results of a Life Cycle Assessment (LCA) of an S-CCHP system that provides space heating, cooling, DHW and electricity. The system consists of hybrid PV-T collectors integrated via two parallel thermal storage tanks with an air-to-water rev-HP. The proposed S-CCHP system is currently in operation in an industrial building located in Zaragoza (Spain). The transient energy model developed to estimate the annual energy outputs has already been validated.

The LCA is performed following ISO standards 14040 and 14044, using SimaPro v9.0.0.49 software and EcoInvent v3.5 database. An LCI is performed with a "*from cradle to grave*" scope, including raw materials, manufacturing processes, transportation and disposal phases. The LCA model is calculated following two methodologies: ReCiPe 2016 Endpoint (H/A) v1.03, and IPCC 2013 GWP 100 years.

The LCA results of the S-CCHP system show that electricity contributes the most to the total environmental impact (77.9%), followed by the PV-T collectors (13%). When electricity is not considered, the PV-T collectors account for 58.7% of the total share, the rev-HP is 20.5%, and the storage tanks are 11.9%. Similar results are obtained following the IPCC GWP 100a method, with electricity accounting for 82.7% of the total $CO_{2eq.}$ emissions, followed by the PV-T collectors (63.5%). In terms of impact category, fine particulate matter formation is the most relevant one, contributing with 46.9% of the total share, followed by global warming (damage to human health, 29.2%).

The LCA results are then compared with a conventional PV-system and a grid-based system, showing that the S-CCHP system has about half of the environmental impacts of the grid-based system. Meanwhile, the PV-system has 30% fewer environmental impacts than the grid-based system. Therefore, it can be concluded that the S-CCHP system appears as a very promising alternative to reduce the environmental impacts associated with the building energy consumption.

In addition, sensitivity analyses are performed to analyse the influence of the system lifetime, the solar irradiance and the power generation mix on the LCA results. First of all, three lifetimes are considered in the current location (Zaragoza, Spain), 10, 15 and 20 years. The S-CCHP system achieves a reduction of $CO_{2\ eq.}$ emissions between 46% and 51% for 10–20 years of system lifetime compared to the grid-based system. Meanwhile, the PV-system only attains a reduction of $CO_{2\ eq.}$ emissions between 24% and 30% for 10–20 years of system lifetime, also compared to the grid-based system. Similar results are obtained using the ReCiPe methodology. The results show that, even if the S-CCHP system has a shorter lifetime than a PV-system (e.g. 10-years lifetime *vs* 15-years lifetime), the S-CCHP system would still reduce more the environmental impacts than the PV-system.

Four alternative climates are selected to analyse the effect of solar irradiance on the LCA results. The results show a 30–32% difference in the environmental impacts of the S-CCHP system between the most suitable climate (Mediterranean) and the least suitable climate (Continental). This difference becomes 25–27% for the PV-system. The difference is attributed to the amount of electricity imported from the grid, lower in the climates with high irradiance levels (the Mediterranean and Cold semi-arid) due to the larger electricity generation of the analysed solar systems.

Finally, four different power generation mixes are considered, from a highly decarbonised electricity grid (Norway) to a fossil-fuel predominant grid (Greece). In all of them, the implementation of the S-CCHP system in an industrial building leads to a reduction of the environmental impacts compared to the grid-based system, from 16% to 26% (depending on the methodology) in Norway to 53–54% reduction in Greece. France and Spain have intermediate values of 36–38% and 49–51%, respectively.

The power generation mix considerably influences the environmental impacts. The results show 6.5–10.4 times larger environmental impacts in Greece than in Norway according to the ReCiPe methodology, and 8.6–15.6 times higher according to the IPCC GWP 100a methodology. This is attributed to the decarbonisation level of the power generation mix in both countries, as in Norway 92% of the grid electricity comes from hydropower, while in Greece 55% of the grid electricity comes from fossil fuels, natural gas and cogeneration.

Therefore, it can be concluded that the proposed S-CCHP system appears as a very promising alternative to reduce the environmental impacts of the building energy consumption in all the analysed geographical locations, even in climates with low irradiance levels or in countries with a highly decarbonised electricity grid (such as Norway).

Further work proposed by the authors includes the integration of the LCA results into ESM to assess the potential of the proposed S-CCHP system and find cost-optimal pathways to achieve the environmental and policy targets set in the EU.

CRediT authorship contribution statement

María Herrando: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Daniel Elduque:** Methodology, Software, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Carlos Javierre:** Validation, Methodology, Resources, Writing – review & editing. **Norberto Fueyo:** Conceptualization, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

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.

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