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Environmental assessment of central solar heating plants with seasonal storage located in Spain

Rosa Gemma Raluy[1], Silvia Guillén-Lambea[1, 2*], Luis M. Serra[1], Mateo Guadalfajara[1], Miguel A. Lozano[1]

[1] Aragón Institute for Engineering Research (I3A), Thermal Engineering and Energy Systems Group (GITSE), University of Zaragoza, Agustín Betancourt Building, C/María de Luna 3, 50018 Zaragoza, Spain

[2] University Center of Defense, Ctra. Huesca, s/n, 50090, Zaragoza, Spain

Abstract

Renewable energies can play a very important role in the development of a new energy model contributing effectively towards a more sustainable development in the mid and long term. In this context Central Solar Heating Plants with Seasonal Storage (CSHPSS) are able to provide space heating and Domestic Hot Water (DHW) to residential buildings with high solar fractions (>50%). These systems are already being used in Central and Northern Europe, as well as in Canada, where there is an important experience in district heating systems. The study presented herein presents an environmental assessment, applying the Life Cycle Assessment (LCA) method, of a CSHPSS, which should cover the space heating and DHW demand of 500 dwellings of 100 m^2, located in Zaragoza, Spain. Environmental burdens through the life cycle of the system are estimated based on greenhouse gas emissions, and comprehensive environmental indicators as the ReCiPe and Cumulative Energy Demand (CED). These indicators allow to evaluate the reduction of the environmental load achieved by the CSHPSS analyzed with respect to conventional space heating and DHW systems, as well as to identify the most critical aspects from the environmental perspective. In this article, the environmental behavior of the CSHPSS is decoupled into the two demands covered, heating and DHW, in order to quantify the environmental impact of each generation system. A detailed life cycle inventory is presented with the aim of promoting the development of increasingly efficient technologies from the environmental point of view, not only in the operation phase but also in the construction of the equipment. Furthermore, an in-depth analysis is performed to evaluate the variation of the environmental impact depending on the climatic conditions. The CSHPSS is also dimensioned in different Spanish cities and a LCA is carried out for nine locations. The results can help different stakeholders to make decisions in order to optimize the renewable energy generation systems taking in account its whole life cycle and to point out the necessity to evaluate the environmental impact essentially in the production phase for all renewable energy systems.

Keywords: Life Cycle Assessment; Solar thermal energy; Seasonal storage; District heating; CSHPSS

NOMENCLATURE

Acronyms

CED Cumulative energy demand
CSHPSS Central solar heating plants with seasonal storage
DD Domestic hot water demand
DHW Domestic hot water
EPS Polystyrene, expandable
EPT Energy payback time
GHG Greenhouse gases
GHP Geothermal heat pump
GWP Global warning potential
HD Heating demand
HPDE: high density polyethylene
IPCC Intergovernmental Panel on Climate Change
ISO International Organization for Standardization
LCA Life cycle assessment
LCI Life cycle inventory
LCIA Life cycle impact assessment
NG Natural gas
PCM Phase change material
PUR: polyurethane TES Thermal energy storage
TTES Tank thermal energy storage
UTES Underground thermal energy storage
XPS Extruded polystyrene

Latin symbols

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[*] Corresponding author. Tel.: +34 976 739838
E-mail address: sguillen@unizar.es

E_P Total electricity input to pumps
E_{P1} Electricity input to pump 1
E_{P2} Electricity input to pump 2
E_{P3} Electricity input to pump 3
E_{PS} Electricity input to solar pump
G Total natural gas supplied to the system
G_{BD} Natural gas input to DHW boiler
G_{BH} Natural gas input to heating boiler
$Q_{a1,l}$ Heat loss from seasonal storage
$Q_{a1,o}$ Heat from seasonal storage
$Q_{a2,l}$ Heat loss from DHW storage
$Q_{a2,o}$ Heat from DHW storage
$Q_{BD,l}$ Heat loss from DHW boiler
$Q_{BD,o}$ Heat output from DHW boiler
$Q_{BH,l}$ Heat loss from heating boiler
$Q_{BH,o}$ Heat output from heating boiler
$Q_{ex1,o}$ Heat output from exchanger 1
$Q_{ex2,o}$ Heat output from exchanger 2
$Q_{ex3,o}$ Heat output from exchanger 3
$Q_{p1,l}$ Heat loss from pump 1
$Q_{p1,o}$ Heat output from pump 1
$Q_{p2,l}$ Heat loss from pump 2
$Q_{p2,o}$ Heat output from pump 2
$Q_{p3,l}$ Heat loss from pump 3
$Q_{p3,o}$ Heat output from pump 3
$Q_{ps,l}$ Heat loss from solar pump
$Q_{ps,o}$ Heat output from solar pump
$Q_{sf,i}$ Energy input to solar field
$Q_{sf,l}$ Heat loss from solar field
$Q_{sf,o}$ Heat output from solar field
SF_{DD} Solar fraction of the DD
SF_{HD} Solar fraction of the HD

Greek symbols

η_{a1} Efficiency of seasonal storage
η_{a2} Efficiency of DHW storage
η_{BH} Efficiency of heating boiler
η_{BD} Efficiency of DHW boiler
η_{sf} Efficiency of solar field

Subscripts

a1 Seasonal storage
a2 DHW storage
p pump
ex exchanger
BH heating boiler

1. Introduction

The progressive depletion of fossil fuels, the growing energy demand, the policies to reduce pollutant emissions, among other reasons, made urgent the search for alternative supply and technology solutions based on renewable energies (Gielen et al., 2019), being solar thermal energy a very interesting future option (International Renewable Energy Agency (IRENA), 2020; Stryi-Hipp et al., 2012). Solar thermal energy presents a great potential for application in the residential-commercial sector, both in small applications (individual houses) and large installations (multi-family dwellings, residential districts, hospitals, commercial buildings, offices, etc.) (IRENA, 2015; Park et al., 2020; Pop et al., 2018; Sánchez-Barroso et al., 2020). The interest and advantages of the application of the solar thermal energy to residential-commercial sector, both for heating and air conditioning, are numerous (International Energy Agency, 2012): important savings in the primary energy consumption and possible reduction of greenhouse gas emissions; diversification of energy sources, both at the end-user level and for the energy planning of a country; increasing the security of energy supply; greater security against variations in the prices of energy resources; decrease in the electricity demand from the network, contributing to the stabilization of the network; reduction of losses by transport due to the production close to the consumption place; in cooling air-conditioning systems, the match between the demand profile and the solar resource availability, which is a key factor in the viability of such systems; the use of solar heat for space heating and production of domestic hot water (DHW) allows to increase the installed capacity getting a high use of the solar thermal systems during all seasons (UNEP, 2014).

Regarding this latter aspect, the use of large systems which combine the solar thermal collectors with seasonal thermal energy storage technology allows to align the largest supply of solar radiation during summer, with the greater energy demand for space heating in winter, being feasible to reach high solar fractions (even higher than 50%) of the combined demand for space heating and DHW (Nielsen, 2011). On the other hand, centralized solar systems can play an important role in the future, due to the special characteristics of the solar thermal energy (free and available at the consumption place). In order to have a complete vision of the interest and advantages of these systems, not only their technical and economic viability should be fulfilled (De Guadalfajara et al., 2012; Lozano et al., 2010; Nielsen, 2011) but also it is necessary to gain a better understanding and knowledge of the potential environmental impacts caused or avoided (environmental benefits) throughout the whole life cycle of the facilities of this type.

To this end, the Life Cycle Assessment (LCA) method can be utilized to analyze the entire range of environmental damages associated with products and services. LCA is an established and internationally standardized method for the analysis and quantification of environmental loads and impacts through the life cycle of products and services (Guinée, 2002). It evaluates the consumption of natural resources and emissions of material flows taking into account all stages in all the life cycle processes (raw material extraction, intermediate and final manufacturing processes, packaging, transport, use and final disposal). By means of quantitative methods of impact assessment (Guinée, 2002; PRe Consultants, 2019), it is evaluated the environmental burden associated with the resource consumption and generated emissions through the life cycle of the analyzed system. The LCA method has been used to analyze the life cycle of products, processes and activities, and has been widely applied to the energy conversion processes, encompassing environmental impacts associated to the fuel consumption as well as the construction, maintenance and final disposal of the components of the plant.

However, there are a relatively limited number of studies which focus on solar thermal systems. Most of these studies analyze the life cycle of solar systems to cover the heating and/or hot water demands of single residential houses (2-5 people) in different locations of European countries (Botsaris et al., 2010; Carnevale et al., 2014; Milousi et al., 2019; Şerban et al., 2016) and North America. This implies that the useful solar collection area and storage systems are small, in any case they do not reach the category of large size solar systems (greater than 500 m^2 collector area (Nielsen, 2011)). (Kalogirou, 2004) focused on presenting the advantages of solar assisted system for single family houses for DHW and space heating and in a more recent paper on presenting the advantages of thermosiphon solar water heaters (Kalogirou, 2009). (Rey-Martínez et al., 2008) developed a LCA of a thermal solar installation with flat collectors for domestic hot water production, built on the roof of a private house and (Mahmud et al., 2018) present a LCA of a solar-photovoltaic (PV) system and a solar-thermal system. (Albizzati and Arese, 2011) studied the environmental impact of solar assisted systems compared with conventional electric or gas systems. (Oró et al., 2012) focused on the DHW storage systems (molten salt and solid medium). (Hang et al., 2012) carried out a comparative LCA of thermal solar systems focused exclusively on the analysis of flat plate collectors and vacuum tubes. Other authors (Albertí et al., 2019; de Laborderie et al., 2011) compare the environmental performance of solar thermal system for providing DHW used in conjunction with complementary heating systems and more conventional scenarios providing the same service (as natural gas heating system).

The CSHPSS technology is an environmentally and sustainable and feasible option, both in warm and Mediterranean climates (Tulus et al., 2016) and in coldest regions (Welsch et al., 2018), where district heating should be featured prominently among other options. This highlights the need to continue investigating the environmental behavior of this technology to position it as a real and effective solution against environmental degradation. Nevertheless, only few works analyze solar thermal application for several dwellings from an environmental point of view (Guillén-Lambea et al., 2020; Nielsen, 2011; Simons and Firth, 2011), (Tulus et al., 2019) perform an environmental assessment of a CSHPSS funding a reduction of the environmental impact from 82.1 to 86.5% for several cities in EU when compared to the use of a more traditional energy source such as natural gas for heating system. (Bartolozzi et al., 2017) perform LCA to assess the environmental sustainability of renewable heating and cooling alternatives for a neighborhood of 1000 inhabitants in Tuscany, Italy, delivered by a district system containing a geothermal heat pump (GHP) and a biomass system obtaining a reduction on GHG emissions about 20% and 35% respectively when compared with the centralised conventional system. (Welsch et al., 2018) analyze the environmental effects of a district heating including a borehole energy storage remarking a decrease of the greenhouse gas emissions of 40% in Germany and (Oró et al., 2012) compare the environmental impact of three different thermal energy storage (TES) systems, including latent heat storage, for solar power plants.

To guarantee the expansion that CSHPSS technology deserves, research on district systems should be promoted, including the rigorous analysis of environmental benefits under different boundary conditions. In this paper a LCA of a hypothetical CSHPSS plant is presented, covering with a high solar fraction (73%) the heating and DHW demand of 500 dwellings of 100 m^2 located in the city of Zaragoza, Spain. The main goal is the estimation of the reduction of the environmental load achieved by the CSHPSS analyzed with respect to conventional space heating and DHW systems, as well as to identify the most critical aspects from an environmental perspective.

Besides the limited studies on the environmental behavior analysis of CSHPSS, none has considered decoupling the environmental loads of the DHW and HD demands, which allows for the identification of the least environmentally efficient equipment. In this research, it has been identified that the generation system associated with heating is less efficient than the one that produces DHW. This conclusion could help to promote or motivate the creation of new future lines of environmental research.

In addition, it has been revealed the difficulty of obtaining data on the manufacture of the equipment to define a realistic and robust Life Cycle Inventory (LCI) of the CSHPPS, since normally these data are rarely published, making the complete analysis of LCA studies difficult. This article presents detailed equipment's

LCIs aiming that they can serve as the basis for future research and promote the advancement in the implementation of environmental analysis methods.

In a second step, the CSHPSS plant is dimensioned for other climatic conditions and the LCA is performed for nine cities in Spain. The comparative results point the solar fraction (SF) as an important parameter which is indicative of the amount of the environmental emissions produced by the whole life of the plant.

2. Methodology

A hypothetical CSHPSS plant is dimensioned to serve 500 dwellings of 100 m^2 in Zaragoza, Spain (41°39'21" N 0°52'38" O). According to the Köppen-Geiger climate type map (Peel et al., 2007), the climate of Zaragoza is arid steppe hot (Climate Bsh) and the global irradiance average per day is 4.79 kWh/m^2 (Sancho et al., 2012) (Spanish meteorology agency (AEMET)). The whole system reaches a high solar fraction (73%) of the space heating and DHW demand. The system has been modeled and developed with the software TRNSYS (Anastasia, 2010; Frago-Moreno, 2011), the designed CSHPSS is presented in Section 2.1.

Remarkable examples of CSHPSS are operating in several countries, e.g. Denmark, Germany or Canada; each plant is unique and has been designed according to the specific characteristics of the location (thermal demands, supply temperature and climatic conditions). However, there is none in Spain, where the higher radiation levels could make them profitable (Guadalfajara, 2016). Therefore, there are no real data from Spanish plants to be able to validate calculation models. The TRNSYS model has been used for the last years by the authors for the investigation of district systems with solar thermal energy (Guadalfajara, 2016), the model has been modified and adapted to current research works dealing with new solar systems configurations. The CSHPSS TRNSYS model results were validated/compared with other calculation methods, including Lunde method (Lunde, 1979), Braun, Klein and Mitchell method (Braun et al., 1981), Drew and Selvage method (Drew and Selvage, 1980), f-Easy method (PlanEnergi, 2014) and Solar district heating online calculation tool (Solites, 2014).

The energy demands incorporated in the model were obtained by extrapolation from direct measurements taken in several dwellings located in a residential area located in Zaragoza. The hourly thermal demands, both for domestic hot water and for heating, were registered and then provided to the TRNSYS model.

In a second step, a complete LCA of the CSHPSS is performed and analyzed providing a comprehensive view of the environmental aspects of the designed system and an accurate picture of the environmental trade-offs in product and process selection. The LCA procedure performed follows the rules standardized by the International Organization for Standardization (ISO) in the ISO 14040 series (ISO 14040; ISO 14042, ISO 14044) (International Organization for Standardization, 2006).

Finally, in a third step the CSHPSS is recalculated for other climatic conditions moving the plant to 9 cities in Spain, the plant is dimensioned according the new climatic data then the LCA is performed and the results compared to assess the incidence of climate data on the design and environmental behavior of district systems.

2.1. Description of the proposed CSHPSS

The system (Figure 1) consists of three main parts: solar field loop, space heating and DHW circuits. The heat exchangers (ex1 and ex2) connect the solar field (primary loop) to the space heating and DHW circuits (secondary circuits), since the primer uses a water-glycol mixture (67/33 weight) as working fluid to protect the solar field of freezing during winter. The energy harvested by the solar collectors is transferred either to the seasonal energy storage or to the DHW storage (preferably to the second).

The seasonal storage tank is a cylindrical water tank built of reinforced concrete. It is connected to the distribution system through a third heat exchanger (ex3) which preheats the return water from the heating network. Due to its large size, the processes of loading and unloading of the seasonal storage tank are significantly slow, which facilitates its function of covering part of the space heating demand during the winter season with the solar thermal energy that has been stored during the summer period.

The DHW storage is an independent tank much smaller than the seasonal storage tank, to get in a few hours of solar heating the temperature required (60º C) for the DHW daily service. This design approach together with the priority of loading of the DHW tank with respect to the seasonal storage tank, allows getting high solar fractions for the DHW. The space heating system produces hot water at 50° C for a district heating network of low temperature.

The system is completed with two auxiliary boilers, which will support and guarantee the coverage of the thermal energy demands when the water temperature in the thermal energy storages is unsatisfactory, several circulation pumps and other auxiliary equipment.

Table 1 shows the monthly operating values of the system. The highest solar irradiance occurs in August. Nevertheless, from March to July the solar field supplies a greater amount of thermal energy to the storage tanks. This can be explained by the fact that the temperature of the hot water in the tank increases from March to September, which reduces the performance of the solar collectors. The solar fraction of the DHW demand (SF_{DD}) exceeds 67% throughout the year, presenting values above 90% during the period from April to October. The solar fraction of the heating demand (SF_{HD}) is very high in the first months of the heating season, when the solar energy captured during the summer period is used. At the beginning of January, the seasonal storage has been completely discharged. From January to March, the heating demand is still important and is mostly generated by the auxiliary boiler. In April, when the heating demand is reduced and the available solar energy exceeds it, the seasonal storage starts charging again, reaching its maximum level in October.

Table 1. Monthly operating values.

	Qsf,i (GJ)	η_{sf} (%)	η_{a1} (%)	η_{a2} (%)	E_P (GJ)*	HD (GJ)	SF_{HD} (%)	DD (GJ)	SF_{DD} (%)	G (GJ)
Jan	974	52.6	92.8	98.5	18	2082	45.8	228	69	1287
Feb	1166	55.5	95.7	98.5	18	1452	33.00	198	74.5	1098
Mar	1529	57.6	96.4	98.5	21	997	65.9	203	79.5	409
Apr	1489	56.7	95.9	98.3	21	333	95.7	167	92.5	28
May	1618	56.4	95.1	98.1	20	0	-	145	93.5	10
Jun	1623	53.4	93.4	98.1	20	0	-	120	90.2	12
Jul	1828	48.3	91.9	97.0	19	0	-	73	97	2
Aug	1872	41.3	89.4	95.0	18	0	-	41	97	1
Sep	1600	32.0	80.0	97.7	14	0	-	102	94.4	6
Oct	1430	31.8	72.0	98.3	15	187	100	149	94.1	9
Nov	1055	44.9	78.0	98.2	16	1200	100	187	74.3	50
Dec	914	50.6	83.5	98.4	15	2380	100	215	67.1	74
YEAR	17098	48.1	90.6	98.2	215	8631	71.6	1828	81.8	2986

* $E_P = E_{PS} + E_{P1} + E_{P2} + E_{P3}$

Figure 1 shows the annual energy balance of the CSHPSS, including the most representative mass and energy flows of the system. The annual thermal energy demand (GD) is 10,459 GJ/year (2,906 MWh/year), being 1,828 GJ/year (508 MWh/year) for domestic hot water and 8,631 GJ/year (2,398 MWh/year) for space heating. To cover these demands, the total power consumption (E) of the pumps is 216 GJ/year (60 MWh/year), and the total natural gas consumption in the auxiliary boilers (G) is 2,986 GJ/year (829.4 MWh/year), being 2,640 GJ/year (733.3 MWh/year) consumed (G_{BH}) in the space heating boiler (93% of efficiency) and 346 GJ/year (96.1 MWh/year) consumed (G_{BD}) in the DHW boiler (96% of efficiency).

Given the features of the energy services that should attend the CSHPSS system, the equipment has been dimensioned and its main technical characteristics are listed in Table 2. For the design of the main system equipment (solar field, thermal energy storages, auxiliary boilers, heat exchangers and pumps), information from commercial manufacturers catalogues and bibliographic information published in the literature has been used (Fabrizio et al., 2009; Oró et al., 2012). Design criteria and procedures are described in detail in the works of (Anastasia, 2010) and (Frago-Moreno, 2011; Frago et al., 2011).

Flat plate collectors have been selected to collect the solar radiation, the proposed aperture area of solar collectors is 2,769m^2, obtaining a ratio with respect to the annual heat demand of A/GD= 0.95 m^2/(MWh/y). The DHW tank was dimensioned based on the daily hot water average demand and its volume was calculated to ensure the hot water demand for two days. The seasonal storage tank volume was designed with the restriction that it should not reject heat at any time and should be fully charged (the temperature of the water in its upper layer is about 100 °C) just before the beginning of the heating season. The heat exchanger surface has been established to guarantee an efficiency of 95% even in the most demanding operating conditions. The sizing of the pumps has been obtained considering the current maximum flow rate and the load losses in the different parts of the hydraulic circuit and finally, the auxiliary boilers were designed to cover by themselves the 100% of the respective heat demands.

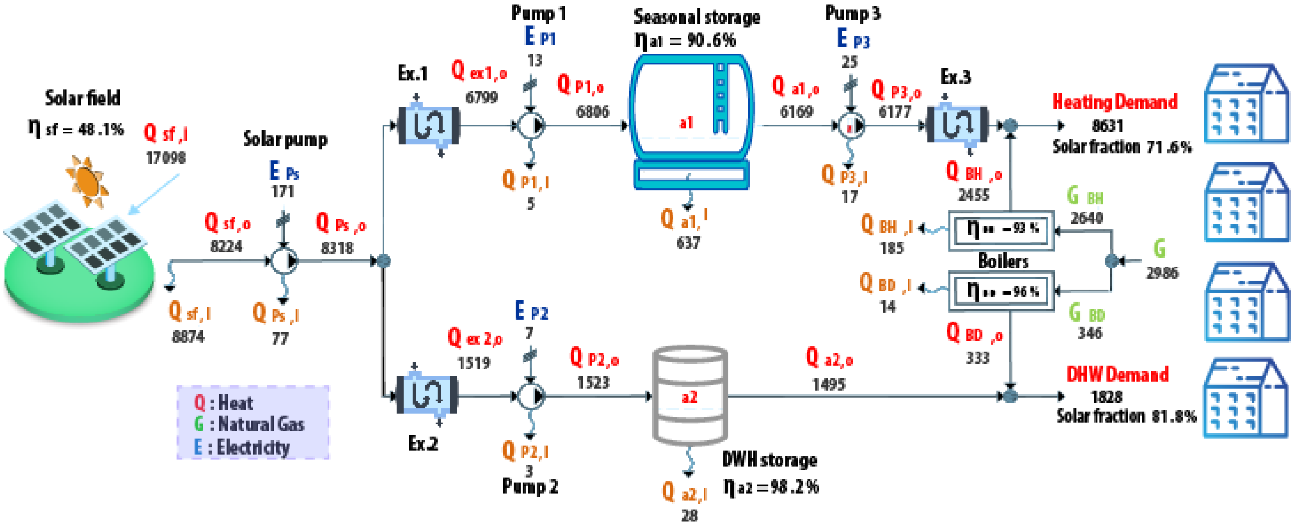

Figure 1. Energy flows of the analyzed system (GJ/year)(Frago et al., 2011)

Table 2. Equipment main technical characteristics.

	Collector area (m^2)	Collector position	Specific flow (kg/hm^2)
Solar collectors	2,769	Slope= 50º Azimuth= 0º	20
Pipes (solar field)	Total length (m)	Diameter (m)	Insulation
	1000	0.1	Thickness= 0.06 m Conductivity= 0.144 kJ/hmK
Storage	Volume (m^3)	Thermal loss (kJ/hm^2K)	Height/ Diameter
Seasonal storage	15,180	0.45	0.6
DHW storage	47	1.6	1.5
Pumps	Nominal Power (kW)	Nominal flow (m^3/h)	
Solar field (Psol)	15.0	54	
P1	1.4	51	
P2	1.4	51	
P3	3.7	104	
Heat exchangers	Efficiency (%)	Area (m^2)	UA (W/m^2K)
ex1	95	282	3942
ex2	95	282	3942
ex3	95	580	3931
Boilers	Thermal capacity (kW)	Efficiency (%)	Service Temp. (ºC)
DHW boiler	208	0.96	60
Heating boiler	1,800	0.93	50

2.2. Life Cycle Assessment and impact methods selection

LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, product disposal, etc.).

The LCA considers a series of four interrelated phases, which follow a specific sequence: i) goal and scope definition, ii) inventory analysis, iii) impact assessment, and iv) interpretation of results. The goal and scope definition of the study establishes the aspects and premises that will be considered in the analysis, as well as the goal by defining the functional unit (or reference performance feature to standardize input and output data) with respect to it will be evaluated the LCA. The inventory analysis is an accounting of the natural resources consumed and the emissions produced "from the cradle to the grave" associated to a) each mass and energy flows that input/output the system, as well as b) each of the pieces of equipment of the plant. The complete system used to develop the LCA includes the input/output flows distribution, especially fuel, and the whole life cycle of the components. Inventories of elementary flows (e.g. consumption of natural resources, energy and emissions generated) are compiled following the international standard approach. The physical conservation laws of mass and energy represent the basis for the calculation of the inventory results. The accuracy of this procedure depends on the assumptions of each modeled process and the full system.

The LCA was carried out with SimaPro software v.9.0.0.35 (PRe Consultants, 2019), utilizing the Ecoinvent 3.5 database (Swiss Centre for Life Cycle Inventories, 2019), and three environmental impact assessment methods. This study analyses the values of the kg of CO_2-equivalent using the IPCC 2013 GWP 100y method (“Intergovernmental Panel on Climate Change - IPCC. Revised supplementary methods and good practice guidance arising from the Kyoto protocol,” 2013), the ReCiPe 2016 method (Huijbregts et al., 2016) and Cumulative Energy Demand (CED) (Huijbregts et al., 2010) methods, since they encompass a large number of environmental aspects of different nature.

The IPCC 2013 method uses the up-to-date figures of the Intergovernmental Panel on Climate Change (IPCC) for the quantification of direct contributions of airborne emissions to the problem of climate change. The method evaluates the emissions of greenhouse gases (GHG) due to anthropogenic activities. The characterization of different gaseous emissions according to their global warming potential and the aggregation of different emissions in the impact category climate change is one of the most widely used methods in life cycle impact assessment (LCIA). Characterization values for GHG emissions are based on global warming potentials (GWPs) published by the IPCC (Intergovernmental Panel on Climate Change, 2014). GWPs are an index for estimating relative global warming contribution due to atmospheric emission of 1 kg of a particular GHG compared to the emission of 1 kg of CO_2, i.e. direct GWPs are relative to the global warming potential of carbon dioxide. Three time horizons are used to show the effects of atmospheric lifetimes of the different gases: GWPs to 20, 100 and 500 years. In this work a timeframe of 100 years has been considered.

CED is a method to calculate Cumulative Energy Demand (expressed in MJ) (Huijbregts et al., 2010), based in the method published by Ecoinvent , available in the SimaPro database. The CED represents the direct and indirect energy use in units of MJ throughout the life cycle of a good, service or product (including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials) (Huijbregts et al., 2010). In addition, this method provides primary energy from renewable and non-renewable sources separately. The method of CED is useful to get a general view of the energy related environmental impacts in a life cycle and for a first comparison of individual products. But energy use does not give a full picture for all environmental impacts in the life cycle of goods and services. Furthermore, the environmental impacts vary among different energy resources, e.g. the impacts of coal use in relation to the energy content are normally more severe than those related to the use of natural gas. Thus, CED analysis cannot be the one and only method for evaluating the environmental impacts of a good or service. It has been included in this work also to estimate the energy payback of the analyzed system.

ReCiPe is a harmonized LCIA method at midpoint (18 midpoint indicators) and endpoint level (3 endpoint indicators), it was first developed in 2008 through cooperation between RIVM, Radboud University Nijmegen, Leiden University and Pré Consultants (Goedkoop et al., 2009; Huijbregts et al., 2016). ReCiPe builds on the Eco- indicator 99 (Gocdkoop et al., 200AD) and the CML Handbook on LCA (2002) (Guinée, 2002).

2.3. LCI of the considered CSHPSS system

The LCA of the analyzed system (see Figure 1) has been divided into assembly or construction and operational phases.

The construction phase is subdivided into each component of the main equipment of the system, which are: solar collectors, seasonal storage, DHW storage, pumps, heat exchangers, pipes and NG boilers. It has been considered for each component: the raw materials, the manufacturing processes of materials and devices, road transportation by lorry and van from the production factory to the location of the system (estimated average distance of 600 km), the land occupation and the final disposal (it is considered that they are dumped to the landfill at the end of its useful life).

Data corresponding to the raw materials of the plant equipment, manufacturing processes and energy consumption have been obtained from commercial manufacturers catalogues and Ecoinvent v3.5 (Swiss Centre for Life Cycle Inventories, 2019) database. Table 3 shows the main materials of the considered devices in the assembly phase of the analyzed solar system and the processes per raw material selected from Ecoinvent.

Table 3. Main materials and process selected of the considered equipment.

Raw material	Process selected (SimaPro 9.0.0.35)	Solar collectors	Seasonal storage	DHW storage	Boilers	Pumps	Heat exchangers	Pipes
Glass (kg)	Solar glass, low-iron {GLO}| market for | APOS, U	20,510	-	-	-	-	-	-
Aluminium (kg)	Aluminium mix (primary 68%, secondary 22%, extruded 10%)	19,520	-	-	-	-	-	-
Copper (kg)	Copper {GLO}| market for | APOS, U	1,700	-	-	-	-	-	-
Rock wool (kg)	Rock wool, fleece, production mix, at plant, density between 30 to 180 kg/m3 RER S	9,264	-	-	-	-	-	-
XPS (kg)	Polystyrene, extruded {GLO}| market for | APOS, U	-	104,950	2,210	-	-	-	-
Concrete (m^3)	Concrete, high exacting requirements {RoW}| market for | APOS, U	-	944.55	19.55		-	-	-
Reinforcing steel (kg)	Reinforcing steel {GLO}| market for | APOS, U	-	818,610	17,230	4,747	-	-	-
Stainless steel (kg)	Steel, chromium steel 18/8 {GLO}| market for | APOS, U	-	32,740	689	-	-	9,352	1,558
PVC (kg)	Polyvinylchloride, suspension polymerised {GLO}| market for | APOS, U	-	5,600	118	-	-	-	-
Cast iron (kg)	Cast iron {RER}| production | APOS, U	-	-	-	-	317	-	-
HDPE (kg)	Polyethylene high density granulate (PE-HD), production mix, at plant RER	-	-	-	-	-	-	738
PUR[3] (kg)	Polyurethane, rigid foam {RER}| market for polyurethane, rigid foam | APOS, U	-	-	-	-	-	-	336

The solar collectors selected for this study are large flat solar collectors currently used in solar heating plants in district heating areas in Denmark. The collector was made by ARCON ("ARCON," 2021) and the raw materials considered in the LCI are based on the supplier data. Solar collectors have seen a significant improvement in performance in recent years and efforts are still being made to keep improving. (Bava et al., 2015) present a study on the performance of the type of collectors used in this research, concluding that efficient components do not always guarantee the best possible performance, unless the entire system is well designed and operated.

The numerous investigations on the development of new technologies for solar collectors are rapidly advancing this field. A detailed study on flat solar collectors is presented by (Colangelo et al., 2016), highlighting advances in new materials, heat-pipe collectors, hybrid PV-solar thermal collectors, geometries and HTF (nanofluids) and identifying the future lines of investigation on innovative solar flat thermal collectors. The development of nanomaterials to increase the efficiency of solar collector is an active research line (Wole-osho et al., 2020), however, there are still some unsolved questions regarding hysteresis, predictability and stability of nanofluids that make the technology not mature enough for large-scale implementation.

The selected seasonal storage is a TTES (tank thermal energy storage), using water as the storage medium, which represents the simplest form of thermal storage, and is the most widespread and technically mature TES technology. For concentrated solar power plants, TTES is also the most commonly deployed but using molten salt as storage fluid. Underground thermal energy storage (UTES) is also very common but its use is conditioned to the geological conditions of the terrain, since it involves heat being stored underground (aquifer, boreholes). The main advantage of UTES systems is that large amounts of thermal energy can be stored across seasons; however, their efficiency is relatively low. Some of the latest progress in thermal energy storage includes the storage in latent energy using phase change materials (PCMs). A review of TES with PCMs, (e.g., PCM emulsions, microencapsulated PCM slurries) was accomplished by (Zalba et al., 2003). Although the use of PCMs is nowadays scientifically developed and, compared to sensible heat storage materials, PCMs have a higher energy density, there are still environmental unknowns which could be a robust motivation for further research. A recent report published by IRENA (IRENA, 2020) provides a summary of the key characteristics and technical attributes of the present and future TES technologies, including thermochemical storage systems. (Zhang et al., 2016) present a deep review of TES system, concluding that thermochemical heat storage (TCS) is still at an early stage of laboratory and pilot research despite its attractive application for long term energy storage. (Alva et al., 2017) summarize TES materials and systems for solar applications including the dynamic performances in recent investigations, and (Ahmed et al., 2017) focused their review on solar thermal energy storage using nanomaterials.

The TTES in this research is representative of the current TES for solar thermal systems in district applications. The tank has reinforced concrete walls, insulated to the outside with extruded polystyrene (XPS) and with a layer of stainless steel in the inner side to avoid vapor diffusion. An additional layer of PVC is placed to protect the insulation from the soil humidity.

Table 4 provides details of the raw materials for solar collector and seasonal storage.

Table 4. Detailed LCI of the solar collector and seasonal storage.

Component	Subassembly	Characteristics	Material	Amount
Solar collector		204 collectors		2,759.75 m^2
		2.27*5.96*0.14 m (external)		
	Absorber	16 elements/ collector	Copper	0.614 kg/m^2 collector
		Length: 0.143 m	Aluminium	1,317 kg/m^2 collector
		Width: 5.787		
		Thickness: 0.5 mm		
	Solar Glass	Aperture area: 15.57 m^2	Glass	7.407 kg/m^2 collector
		Thickness: 3.2 mm		
	Insulation	Thickness: 75 mm and 30 mm	rock wool	3.345 kg/m^2 collector
		Aperture dimensions: 2.197 *5.721 m		
	Box		Aluminium	5.733 kg/m^2 collector
Seasonal storage (TTES)		H: 19.09 m; D: 31.817 m		capacity: 15,180 m^3
	Insulation	30 cm (side wall)	Concrete	944.55 m^3
			reinforced steel	818.61 ton
		20 cm	XPS	104.95 ton
	Internal layer	1.2 mm	Stainless steel	32.74 ton
	External layer	2 mm	PVC	5.6 ton

In the operational phase the electrical power consumption of the pumps and the NG consumption in the auxiliary boilers have been considered, but not the maintenance of the equipment. For electric energy, the values of the electric energy production mix in Spain for the year 2019 (Red eléctrica de España, 2019) have been entered in SimaPro (nuclear 22%, eolic 21%, combined cycle 20%, cogeneration 12%, hydraulic 10.5%, coal 4.2%, solar photovoltaic 3.5%, solar thermal 2 %, others renewable 1.4%, others 3.4%).

For natural gas, a new process has been generated in SimaPro which estimates, on the one hand, the environmental impact of the combustion of natural gas and on the other, the gas distribution system, which in the case of Spain, the majority basically comes from Algeria (Carvalho, 2011). This process has been used for IPCC 2013 and ReCiPe methods, however for CED method the final to primary energy conversion factors for Spain have been used (Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2014).

The functional unit (calculation basis) for the analysis is 1 MWh of the thermal energy produced for the plant, the useful lifetime considered of the plant is 25 years except for the thermal energy storages which have a lifetime of 50 years. The limit of the analyzed system is set in the distribution network, i.e. it is out the scope of this study the district heating network needed to transport the heat to the dwellings.

In respect to the recycling/reuse of materials at the end of their lifetime, the selected processes of Ecoinvent database related to material include recycling rate in their production: 44% in copper, 37% steel stainless, 35% cast iron, 37% reinforced steel, 32% aluminium, 15% Al-Cu allow.

3. Results and discussions

The separate study of the effect of manufacturing the main devices (construction), and their operation allows the identification of the system components and stages with greater environmental relevance, providing information on possible improvements. It also shows the environmental loads associated to the solar subsystem and to the auxiliary subsystem.

Table 5 presents airborne emissions of GHG evaluated in terms of CO_2 equivalent emissions according to IPCC 2013 considering a time horizon of 100 years. Besides, it is shown the punctuation obtained with the impact assessment method ReCiPe, as well as the involved energy evaluated with the Cumulative Energy Demand, CED, method. Figure 2 represents the relative impacts in percentages of the solar and auxiliary subsystems, as well as the breakdown of the solar subsystem.

Table 5. Relevant airborne emissions and values of ReCipe and CED per unit of total thermal energy demand.

	IPCC 2013	ReCiPe 2016 Endpoint (H)				CED
	kg CO_2 eq/MWh	Human health (Pt/MWh)	Ecosystem (Pt/MWh)	Resources (Pt/MWh)	Total (Pt/MWh)	MWh CED/MWh
Solar collectors	3.25	0.25	0.01	1.68E-03	0.26	0.02
Seasonal storage	25.39	1.18	0.06	0.01	1.26	0.08
DHW storage	0.53	2.48E-02	1.26E-03	2.61E-04	0.03	1.59E-03
Pumps	0.01	9.69E-04	3.15E-05	7.38E-06	0.00	4.64E-05
Heat exchangers	0.61	4.85E-02	1.69E-03	3.32E-04	0.05	2.38E-03
Pipes	0.15	9.91E-03	4.01E-04	1.27E-04	1.04E-02	7.92E-04
Electricity (pumps)	4.05	1.59E-01	1.52E-02	2.74E-03	0.18	0.05
SOLAR SUBSYSTEM	**33.99**	**1.68**	**0.09**	**0.02**	**1.79**	**0.14**
Boilers	0.22	1.21E-02	5.60E-04	1.26E-04	0.01	7.55E-04
Natural Gas	79.79	1.56	0.14	0.06	1.76	0.34
AUXILIARY SUBSYSTEM	**80.02**	**1.57**	**0.14**	**0.07**	**1.78**	**0.34**
TOTAL SYSTEM	**114.01**	**3.25**	**0.23**	**0.08**	**3.56**	***0.48***

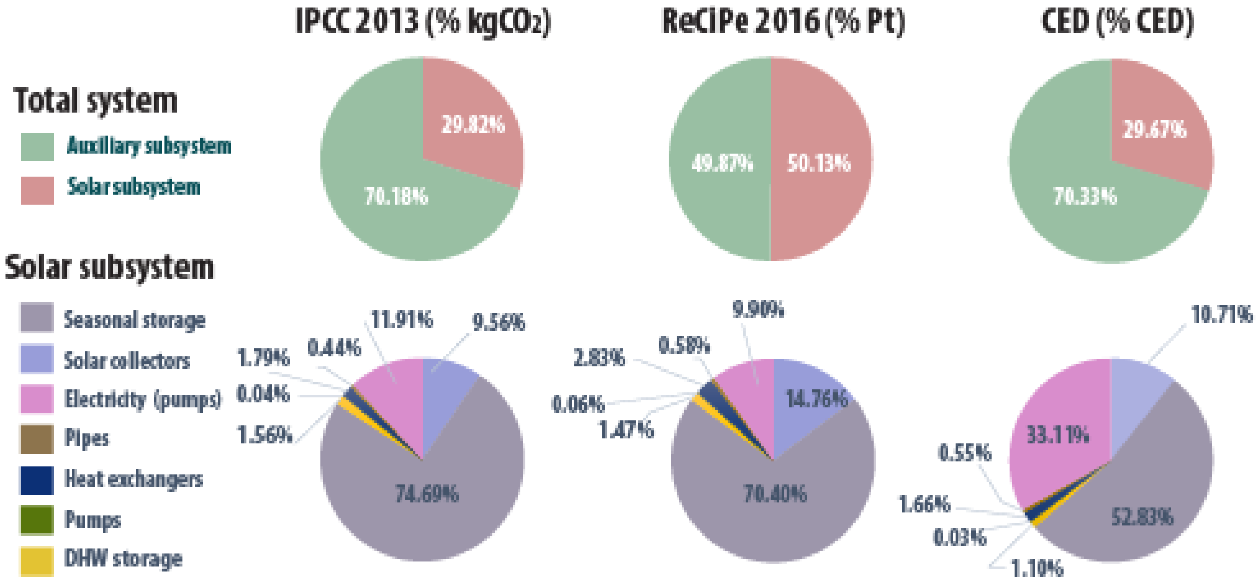

Figure 2. Results in percentage of the three impact assessment methods

Greenhouse gas emissions (expressed in kg CO_2-eq per MWh of total thermal energy demand) are mainly associated to the auxiliary subsystem due to the natural gas consumption, being almost negligible the contribution of some equipment as the boilers. Focusing on the solar subsystem, the seasonal storage is the component that provokes the highest emissions of CO_2-eq exceeding 74% of the emission associated to the subsystem. The electricity consumed by the pumps is the second item producing higher emissions of CO_2-eq reaching almost 12%. The solar field presents a significant lower contribution in terms of CO_2-eq (9%)

emissions. Thanks to the solar subsystem the utilization of the gas boilers as well as the consumption of natural gas are significantly reduced.

The emissions provoked by the solar collectors are mainly due to the aluminum, glass and copper, and those provoked by the seasonal storage tank are mainly due to the reinforcing steel and the polystyrene extruded. These results are in accordance with those obtained in other LCA studies, the copper and aluminum materials of solar collectors present the highest environmental burden in the works of (Allen et al., 2010), (Battisti and Corrado, 2005) and (Martinopoulos et al., 2013), as well as in the solar wall systems studied by (Stazi et al., 2012). The thermal storage water tank is the main responsible of environmental loads in the works developed by (Tsilingiridis et al., 2004) and (Koroneos and Nanaki, 2012).

Analyzing the ReCiPe 2016 method results, which provide a broad picture of the environmental burden, the solar and auxiliary subsystems cause similar environmental impacts, practically half each of them. However, the second subsystem generates only 30% of the energy. The environmental impacts generated by seasonal accumulation stand out negatively, followed very far by those generated by solar collectors, the impacts caused by the rest of the equipment being negligible. On the other hand, it should be noted that the human health indicator is much more important than the other two indicators, representing 91% of the impact compared to 6% for the ecosystem and 2% for resources indicators.

In terms of the direct and indirect energy use throughout the life cycle CED, the auxiliary system presents significantly higher values due to the natural gas consumption, which represents the 80% of the total CED. Nevertheless, analyzing the values corresponding to the solar subsystem, the seasonal storage tank is the component that requires the highest amount of energy (around 53%) throughout its life cycle; followed by the electricity consumed by the pumps (33%), and the solar collector (11%). As in the previous environmental indicators, the contribution of the rest of equipment is not significant. Figure 3 shows the CED from renewable and non-renewable sources for the solar subsystem. CED from renewable sources is almost 14% of the total solar subsystem, it should be noted that most of it, 9% is due to electricity consumption, 2.4% to solar collectors and almost 2% to seasonal storage. The CED allows to estimate the Energy Payback Time (EPT) of the analyzed system, which is relevant for the assessment of systems driven by renewable energies. The EPT is the period of time in which the system has to be in operation in order to save the amount of primary energy that has been spent for production, operation and maintenance of the system (Streicher et al., 2004). According to this, the Energy Payback Time is 6.3 years, which is significantly lower than the useful plant lifetime.

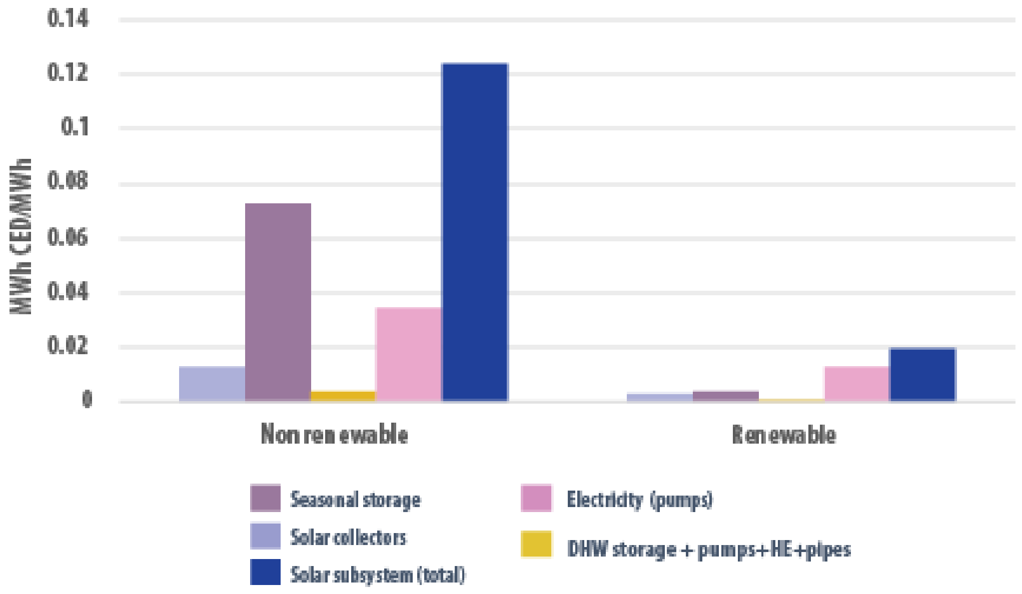

Figure 3.CED renewable/no renewable of the Solar Subsystem

The environmental burden has also been analyzed considering separately the space heating and DHW demands. The results are shown in Table 6 and Figure 4. The environmental loads of the solar field, solar pump and pipe, which are common to both subsystems (space heating and DHW) have been apportioned proportionally to the thermal energy produced by the solar subsystem to cover the space heating and DHW demands. The proposed analysis has the advantage that it associates the environmental loads generated by each equipment with the final energy that the equipment helps to produce. Actually, this form of data processing is more correct since it determines the least efficient equipment from an environmental point of view. The environmental loads obtained with the three methods reveal that the energy generation system for heating is much less efficient from an environmental point of view than the DHW generation system, almost doubling the values obtained in the three methods. Once again, seasonal storage is revealed as the most polluting and least efficient element from an energy point of view, with 59% MWh CED / MWh.

Table 6. Relevant CO_2 emissions and points of ReCiPe and CED per space heating and per DHW energy demands.

		IPCC 2013 GWP 100a (kg CO2 eq/MWh)		ReCiPe 2016 Endpoint (H) Total (Pt/MWh)		CED (MWh CED/MWh)	
		By MWh of HEATING	By MWh of DHW	By MWh of HEATING	By MWh of DHW	By MWh of HEATING	By MWh of DHW
	Solar collectors	3.17	3.62	0.26	0.29	1.50E-02	1.72E-02
	Seasonal storage	30.78		1.52		9.21E-02	
	DHW storage		3.04		0.15		9.07E-03
Pumps	*Pump 1*	3.20E-03		2.54E-04		1.17E-05	
	Pump 2		1.51E-02		1.20E-03		5.52E-05
	Pump 3	3.68E-03		2.93E-04		1.35E-05	
	Solar Pump	4.25E-03	4.86E-03	3.38E-04	3.86E-04	1.56E-05	1.78E-05
Heat exchangers	*Heat exchanger 1*	0.21		1.72E-02		8.12E-04	
	Heat exchanger 2		0.98		8.11E-02		3.83E-03
	Heat exchanger 3	0.32		2.69E-02		1.27E-03	
	Pipes	0.15	0.17	1.02E-02	1.16E-02	7.72E-04	8.82E-04
Electricity	*Pump 1*	0.30		1.29E-02		3.47E-03	
	Pump 2		0.75		3.28E-02		8.81E-03
	Pump 3	0.57		2.48E-02		6.68E-03	
	Solar Pump	3.13	3.57	0.14	0.16	3.67E-02	4.20E-02
	SOLAR SUBSYSTEM	**38.62**	**12.15**	**2.01**	**0.73**	**0.16**	**0.08**
Boilers	*Boiler heating*	0.24		1.40E-02		8.28E-04	
	Boiler DHW		0.12		0.01		4.14E-04
Natural Gas	*Heating*	85.51		1.89		0.36	
	DHW		52.83		1.17		0.23
	AUXILIARY SUBSYSTEM	**85.76**	**52.96**	**1.90**	**1.18**	**0.37**	**0.23**
	TOTAL SYSTEM	**124.38**	**65.10**	**3.92**	**1.90**	**0.52**	**0.31**

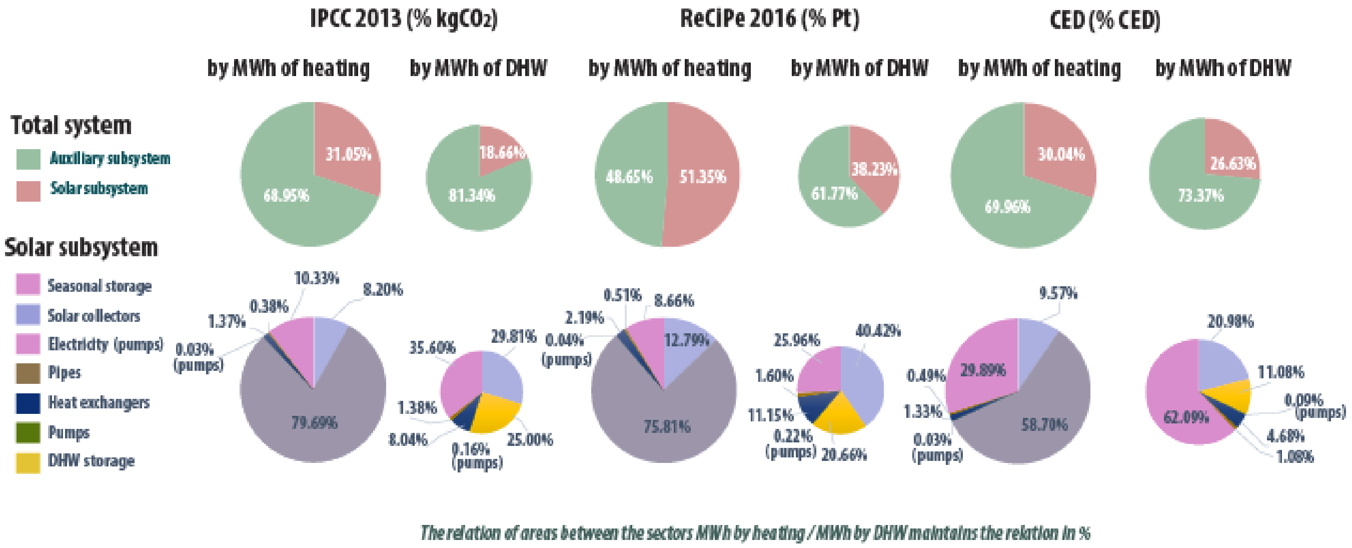

Figure 4. Results in percentage of the three impact assessment methods per space heating and per DHW energy demands

3.1. Sensitivity to climatic conditions

The effect of the different geographical location of the plant on the environmental impact has been studied, selecting Spanish cities located at different climatic conditions. According to Spanish standards (Ministerio de Fomento, 2017), there are 5 winter climatic zones in the country depending on the winter severity index, they are named with letters from A (warmer) to E (coldest) and 4 summer climatic zones depending on the summer severity index named with numbers from 1 (less severity) to the 4 (hottest). Spanish cities with high annual heating demand (> 25 kWh/m^2) representative for winter climatic zones C, D and E have been selected.

System dimensioning has been performed for each city (Table 7), keeping constant the number of dwellings (500) and the ratio A/GD (0.95), but the ratio V/A has been calculated to optimize the seasonal storage volume in order to be fully charged at the beginning of the heating period.

The sizing pumps (mass flow, power and weight) and its electricity consumption have been obtained proportionally to the base case pumps. The solar pump flow has been calculated according to the collector solar area; and flows for pumps 1, 2 and 3 considering the energetic flow $Q_{P3,o}$ (P1, P3) and $Q_{a2,o}$ (P2).

Radiation values are from Spanish meteorological agency (Sancho et al., 2012).

Solar field area is calculated proportional at the case base solar field area depending on the energy demand in the city.

Table 7. Technical data from several cities in Spain (A/GD=0.95).

	Zaragoza	Jaén	Barcelona	Oviedo	La Coruña	Salamanca	Vitoria	Burgos	Soria
Climatic zone	D3	C4	C2	C1	C1	D2	D1	E1	E1
GSr (kWh/m^2)	1,582	1,612	1,369	1,105	1,166	1,501	1,146	1,379	1,470
V/A (m^3/m^2)	5.5	6.7	4.8	2.6	3.8	6.2	4.0	5.0	5.5
V/DD (m^3/(MWh/d))	34	28	27	26	26	26	26	25	25
Heating (MWh/y)	2,397.50	1,547.19	1,671.20	2,852.26	1,771.59	3,679	2,862.06	4,553	4,257.72
DWH (MWh/y)	507.78	484.1	503.78	523.46	511.65	531.33	531.33	543.14	539.21
Total demand (MWh/y)	2,905.28	2,031.29	2,174.98	3,375.72	2,283.24	4,210.33	4,393.39	5,096.12	4,796.93
SF (%)	73.38	88.18	75.91	49.65	58.53	76.35	54.96	60.63	66.11
primary NG (MWh/y)	828.41	366.04	594.34	1850.00	1009.45	1178.00	2125.96	2114.46	1742.28
electricity (kWh/y)	60.00	44.35	45.18	62.15	44.69	86.87	82.73	98.27	96.37
solar field area (m^2)	2,770	1,941	2,077	3,217	2,172	4,005	4,181	4,846	4,561
seasonal storage (m^3)	**15,180**	**12,929**	**9,918**	**8,338**	**8,242**	**24,799**	**16,695**	**24,207**	**25,064**
DWH storage (m^3)	47.30	46.42	46.93	47.33	47.66	46.58	46.58	47.62	47.27

The area of the solar field varies from 1,941 m^2 in Jaén to 4,846 m^2 in Burgos. Regarding storage, DHW storage volume presents very small variations, while the volume of seasonal storage varies between 8,242 m^3 for the city of La Coruña and 25,064 m^3 for Soria. Due to the relevance of the seasonal storage in the case of Zaragoza (≈74% of GHG total emissions in the solar subsystem, see Table 5), a detailed study has been done to determine the LCA for a wide variation of seasonal storage volume based on the existing data from several European storage systems in solar plants. Table 8 presents the main materials (LCI) of several seasonal storages. The construction and design of each specific TES application must be optimized to obtain the thermal storage capacity required. Nevertheless, the different construction materials used on real functioning projects are presented with the aim of evaluating the environmental impact caused by each one of them. The objective is to motivate a change in the optimization guidelines for thermal equipment, where the environmental impact generated in the short term should be included as an important design parameter, as well as mechanical resistance and thermal capacity.

Table 9 shows the environmental impact obtained from SimaPro applying the three selected methods. Values are calculated for a lifetime of 50 years, and presented for the construction of the seasonal storage and for m^3 of their capacity.

Table 8. Main materials of several seasonal storages.

	Ilmenau	Crailsheim	Rottweil	Studsvik	Hannover	Hamburg	Munich	Lombohov	Friedrischs-hafen	Base case
V (m^3)	300	480	600	800	2,750	4,500	6,000	10,000	12,000	15,178
concrete (m^3)	-	97.74	78.03	148.50	306.45	445.5	486	472.5	754.92	944.55
reinforcing steel (ton)	-	84.71	67.63	128.7	265.59	386.1	421.2	409.5	654.26	818.61
XPS (ton)	-	-	-	-	-	-	-		83.88	104.95
stainless steel	-	4.23	1.13	-	-	16.09	17.55	-	27.26	32.74
PVC (ton)	-	-	-	-	-	-	-	-	4.47	5.6
PUR (ton)	2.25	-	-	1.62	-	-	-	10.72	-	-
UP (ton)	49.52	-	-	-	-	-	-	-	-	-
glass recycled (ton)	-	5.09	-	-	22.7	-	36.9	-	-	-
foam glass (ton)	-	0.37	-	-	-	-	8.1	-	-	-
rock wool (ton)	-	-	6.81	-	-	22.275	-	-	-	-
rubber (ton)	-	-	-	1.32	-	-	-	4.2	-	-
HPDE (ton)	-	-	-	1.155	-	-	-	-	-	
EPS (ton)	-	-	0.8	-	-	-	-	-	-	-
Light-weight concrete (ton)	-	-	-	-	-	-	-	327.35	-	-

Table 9. Environmental impacts of several seasonal storages: IPCC, ReCiPe and CED. Yearly values for a lifetime of 50 years

	Ilmenau	Crailsheim	Rottweil	Studsvik	Hannover	Hamburg	Munich	Lombohov	Friedrischs-hafen	Base case
V (m^3)	300	480	600	800	2.750	4.500	6.000	10.000	12.000	15.178
kg $CO_{2\ eq}$	4.381,13	5.881,10	7.045,67	8.308,42	17.516,51	26.035,18	29.940,00	30.773,91	60.706,22	74.268,64
kg $CO_{2\ eq}$ /m^3	14,60	12,25	11,74	10,39	6,37	5,79	4,99	3,08	5,06	4,89
Pt	178,82	340,42	342,97	459,17	980,46	1.509,49	1.712,96	1.646,20	2.978,18	3.660,80
Pt/m^3	0,60	0,71	0,57	0,57	0,36	0,34	0,29	0,16	0,25	0,24
MWh CED	21,96	18,09	25,14	25,28	53,41	77,86	92,88	94,54	182,51	220,42
MWh CED/m^3	0,07	0,04	0,04	0,03	0,02	0,02	0,02	0,01	0,02	0,01

The emissions associated at each location for construction phase have been calculated as follow:

- Seasonal storage: based on the environmental data obtained per m^3 of seasonal storage, for those storage volumes between that of Jaen (12,929 m^3) and that of Soria (25,064 m^3), the environmental data for m^3 from the base case (Zaragoza) have been proportionally applied and for those between 8000 and 10,000 m^3, the data for m^3 obtained for the Lombohov seasonal storage with 10,000 m^3 capacity have been applied, as an example of reduced environmental emissions;
- Solar field: the emissions are calculated proportionally to m^2 of solar field of case base (Zaragoza), therefore the environmental parameters per MWh of energy demand are the same for all the cities;
- Pumps: emissions are proportional to weight of the case base pumps considering the energetic flows $Q_{P3,o}$ and $Q_{a2,o}$ (see Figure 2);
- Heat exchangers: emissions are proportional to m^2 of the case base exchangers surfaces considering the energetic flows $Q_{P3,o}$ and $Q_{a2,o}$;
- Boilers: environmental impacts are proportional to weight of the case base boilers;
- Pipes: environmental impacts remain invariable are calculated per MWh/y of energy demand.

For operation phase, the emissions due to the pumps electricity and the NG boilers consumptions have been obtained from SimaPro. The results from the IPCC 2013 GWP 100a method are shown in Table 10, for the ReCipe in Table 11 and for CED in Table 12.

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Table 10. kg CO2-eq emissions per MWh of total thermal energy demand for different Spanish cities.

	Zaragoza		Jaén		Barcelona		Oviedo		La Coruña		Salamanca		Vitoria		Burgos		Soria	
	kg $_{\mathrm{CO2\ eq}}$/ MWh	%	kg $_{\mathrm{CO2\ eq}}$/ MWh	%	kg $_{\mathrm{CO2\ eq}}$/ MWh	%	kg $_{\mathrm{CO2\ eq}}$/ MWh	%	kg $_{\mathrm{CO2\ eq}}$/ MWh	%	kg $_{\mathrm{CO2\ eq}}$/ MWh	%	kg $_{\mathrm{CO2\ eq}}$/ MWh	%	kg $_{\mathrm{CO2\ eq}}$/ MWh	%	kg $_{\mathrm{CO2\ eq}}$/MWh	%
Solar collectors	3,25	*9,56%*	3,26	*8,08%*	3,26	*14,23%*	3,26	*20,86%*	3,26	*16,57%*	3,26	*8,76%*	3,26	*12,28%*	3,26	*10,44%*	3,26	*9,65%*
Seasonal storage	25,39	*74,69%*	31,12	*77,27%*	14,04	*61,31%*	7,61	*48,71%*	11,12	*56,50%*	28,80	*77,44%*	18,58	*70,00%*	23,23	*74,35%*	25,55	*75,67%*
DHW storage	0,53	*1,56%*	0,75	*1,85%*	0,70	*3,07%*	0,46	*2,93%*	0,68	*3,46%*	0,36	*0,97%*	0,35	*1,30%*	0,31	*0,98%*	0,32	*0,95%*
Pumps	0,01	*0,04%*	0,01	*0,03%*	0,01	*0,06%*	0,01	*0,07%*	0,01	*0,06%*	0,01	*0,03%*	0,01	*0,04%*	0,01	*0,04%*	0,01	*0,04%*
Heat exchangers	0,61	*1,79%*	0,64	*1,60%*	0,61	*2,67%*	0,54	*3,48%*	0,58	*2,93%*	0,61	*1,64%*	0,56	*2,09%*	0,57	*1,82%*	0,59	*1,75%*
Pipes	0,15	*0,44%*	0,22	*0,53%*	0,20	*0,88%*	0,13	*0,83%*	0,19	*0,97%*	0,10	*0,28%*	0,10	*0,37%*	0,09	*0,27%*	0,09	*0,27%*
Electricity (pumps)	4,05	*11,91%*	4,28	*10,63%*	4,07	*17,78%*	3,61	*23,12%*	3,84	*19,51%*	4,05	*10,88%*	3,69	*13,91%*	3,78	*12,10%*	3,94	*11,67%*
SOLAR SUBSYSTEM	**33,99**	***29,82%***	**40,28**	***44,34%***	**22,91**	***23,00%***	**15,62**	***9,22%***	**19,68**	***13,69%***	**37,19**	***32,14%***	**26,55**	***16,35%***	**31,24**	***21,15%***	**33,77**	***24,89%***
Boilers	0,22	*0,28%*	0,14	*0,28%*	0,21	*0,28%*	0,43	*0,28%*	0,34	*0,28%*	0,22	*0,28%*	0,38	*0,28%*	0,32	*0,28%*	0,28	*0,28%*
Natural Gas	79,79	*99,72%*	50,43	*99,72%*	76,47	*99,72%*	153,36	*99,72%*	123,72	*99,72%*	78,30	*99,72%*	135,42	*99,72%*	116,11	*99,72%*	101,64	*99,72%*
AUXILIARY SUBSYSTEM	**80,02**	***70,18%***	**50,57**	***55,66%***	**76,68**	***77,00%***	**153,79**	***90,78%***	**124,07**	***86,31%***	**78,51**	***67,86%***	**135,79**	***83,65%***	**116,43**	***78,85%***	**101,92**	***75,11%***
TOTAL SYSTEM	**114,01**	***100,00%***	**90,85**	***100,00%***	**99,59**	***100,00%***	**169,41**	***100,00%***	**143,75**	***100,00%***	**115,71**	***100,00%***	**162,34**	***100,00%***	**147,68**	***100,00%***	**135,69**	***100,00%***

Table 11. Environmental impact according to ReCiPe 2016 (Pt per MWh of total thermal energy demand) for different Spanish cities.

	Zaragoza		Jaén		Barcelona		Oviedo		La Coruña		Salamanca		Vitoria		Burgos		Soria	
	Pt/MWh	%	Pt/MWh	%	Pt/MWh	%	Pt/MWh	%	Pt/MWh	%	Pt/MWh	%	Pt/MWh	%	Pt/MWh	%	Pt/MWh	%
Solar collectors	0,26	*14,76%*	0,26	*12,65%*	0,26	*20,74%*	0,26	*29,50%*	0,26	*23,87%*	0,26	*13,66%*	0,26	*18,70%*	0,26	*16,10%*	0,26	*14,93%*
Seasonal storage	1,26	*70,40%*	1,53	*73,28%*	0,73	*57,36%*	0,40	*44,20%*	0,58	*52,28%*	1,41	*73,22%*	0,91	*64,79%*	1,14	*69,59%*	1,25	*71,19%*
DHW storage	2,63E-02	*1,47%*	3,69E-02	*1,77%*	3,49E-02	*2,74%*	2,26E-02	*2,53%*	3,37E-02	*3,05%*	1,79E-02	*0,93%*	1,71E-02	*1,22%*	1,51E-02	*0,92%*	1,59E-02	*0,90%*
Pumps	1,01E-03	*0,06%*	1,07E-03	*0,05%*	1,01E-03	*0,08%*	8,98E-04	*0,10%*	9,55E-04	*0,09%*	1,01E-03	*0,05%*	9,19E-04	*0,07%*	9,41E-04	*0,06%*	9,80E-04	*0,06%*
Heat exchangers	5,05E-02	*2,83%*	5,34E-02	*2,56%*	5,08E-02	*4,00%*	4,50E-02	*5,04%*	4,79E-02	*4,33%*	5,05E-02	*2,61%*	4,61E-02	*3,27%*	4,72E-02	*2,88%*	4,92E-02	*2,79%*
Pipes	1,04E-02	*0,58%*	1,49E-02	*0,72%*	1,39E-02	*1,10%*	8,98E-03	*1,00%*	1,33E-02	*1,20%*	7,20E-03	*0,37%*	6,90E-03	*0,49%*	5,95E-03	*0,36%*	6,32E-03	*0,36%*
Electricity (pumps)	0,18	*9,90%*	0,19	*8,97%*	0,18	*13,99%*	0,16	*17,63%*	0,17	*15,17%*	0,18	*9,15%*	0,16	*11,46%*	0,17	*10,08%*	0,17	*9,77%*
SOLAR SUBSYSTEM	**1,79**	***50,13%***	**2,08**	***64,99%***	**1,27**	***42,75%***	**0,89**	***20,75%***	**1,10**	***28,62%***	**1,93**	***52,54%***	**1,41**	***31,82%***	**1,64**	***38,78%***	**1,76**	***43,76%***
Boilers	0,01	*0,72%*	0,01	*0,72%*	0,01	*0,72%*	0,02	*0,72%*	0,02	*0,72%*	0,01	*0,72%*	0,02	*0,72%*	0,02	*0,72%*	0,02	*0,72%*
Natural Gas	1,76	*99,28%*	1,12	*99,28%*	1,69	*99,28%*	3,39	*99,28%*	2,74	*99,28%*	1,73	*99,28%*	2,99	*99,28%*	2,57	*99,28%*	2,25	*99,28%*
AUXILIARY SUBSYSTEM	**1,78**	***49,87%***	**1,12**	***35,01%***	**1,70**	***57,25%***	**3,42**	***79,25%***	**2,76**	***71,38%***	**1,74**	***47,46%***	**3,02**	***68,18%***	**2,59**	***61,22%***	**2,26**	***56,24%***
TOTAL SYSTEM	**3,56**	***100,00%***	**3,21**	***100,00%***	**2,98**	***100,00%***	**4,31**	***100,00%***	**3,86**	***100,00%***	**3,67**	***100,00%***	**4,42**	***100,00%***	**4,22**	***100,00%***	**4,03**	***100,00%***

Table12. CED per MWh of total thermal energy demand for different Spanish cities.

	Zaragoza		Jaén		Barcelona		Oviedo		La Coruña		Salamanca		Vitoria		Burgos		Soria	
	MWh CED/ MWh	%	MWh CED/ MWh	%	MWh CED/ MWh	%	MWh CED/ MWh	%	MWh CED/ MWh	%	MWh CED/ MWh	%	MWh CED/ MWh	%	MWh CED/ MWh	%	MWh CED/ MWh	%
Solar collectors	0,02	*10,71%*	0,02	*14,30%*	0,02	*16,80%*	0,02	*21,90%*	0,02	*18,77%*	0,02	*15,33%*	0,02	*15,29%*	0,02	*17,31%*	0,02	*13,05%*
Seasonal storage	0,08	*52,83%*	0,06	*45,50%*	0,05	*38,30%*	0,02	*27,04%*	0,04	*33,88%*	0,06	*45,13%*	0,04	*37,80%*	0,05	*41,10%*	0,05	*44,39%*
DHW storage	1,59E-03	*1,10%*	2,23E-03	*1,59%*	2,10E-03	*1,77%*	1,37E-03	*1,50%*	2,04E-03	*1,91%*	1,08E-03	*0,83%*	1,03E-03	*1,03%*	9,11E-04	*0,79%*	9,61E-04	*0,82%*
Pumps	4,64E-05	*0,03%*	4,91E-05	*0,04%*	4,67E-05	*0,04%*	4,14E-05	*0,05%*	4,40E-05	*0,04%*	4,64E-05	*0,04%*	4,23E-05	*0,04%*	4,33E-05	*0,04%*	4,51E-05	*0,04%*
Heat exchangers	2,38E-03	*1,66%*	2,52E-03	*1,80%*	2,40E-03	*2,01%*	2,13E-03	*2,33%*	2,26E-03	*2,12%*	2,38E-03	*1,83%*	2,17E-03	*2,16%*	2,23E-03	*1,93%*	2,32E-03	*1,97%*
Pipes	7,92E-04	*0,55%*	1,13E-03	*0,81%*	1,06E-03	*0,89%*	6,81E-04	*0,75%*	1,01E-03	*0,95%*	5,46E-04	*0,42%*	5,23E-04	*0,52%*	4,51E-04	*0,39%*	4,79E-04	*0,41%*
Electricity (pumps)	0,05	*33,11%*	0,05	*35,97%*	0,05	*40,20%*	0,04	*46,45%*	0,05	*42,33%*	0,05	*36,43%*	0,04	*43,16%*	0,04	*38,45%*	0,05	*39,33%*
SOLAR SUBSYSTEM	**0.14**	***29.67%***	**0.14**	***39.38%***	**0.12**	***26.72%***	**0.09**	***12.24%***	**0.11**	***16.78%***	**0.13**	***28.07%***	**0.10**	***14.81%***	**0.12**	***18.90%***	**0.12**	***21.33%***
Boilers	7.55E-04	*0.22%*	4.77E-04	*0.22%*	7.24E-04	*0.22%*	1.45E-03	*0.22%*	1.17E-03	*0.22%*	7.41E-04	*0.22%*	1.28E-03	*0.22%*	1.10E-03	*0.22%*	9.62E-04	*0.22%*
Natural Gas	0.34	*99.78%*	0.21	*99.78%*	0.33	*99.78%*	0.65	*99.78%*	0.53	*99.78%*	0.33	*99.78%*	0.58	*99.78%*	0.49	*99.78%*	0.43	*99.78%*
AUXILIARY SUBSYSTEM	**0.34**	***70.33%***	**0.22**	***60.62%***	**0.33**	***73.28%***	**0.65**	***87.76%***	**0.53**	***83.22%***	**0.33**	***71.93%***	**0.58**	***85.19%***	**0.50**	***81.10%***	**0.43**	***78.67%***
TOTAL SYSTEM	***0.48***	***100.00%***	**0.36**	***100.00%***	**0.45**	***100.00%***	**0.75**	***100.00%***	**0.63**	***100.00%***	**0.46**	***100.00%***	**0.68**	***100.00%***	**0.61**	***100.00%***	**0.55**	***100.00%***

Analyzing Table 10, in all cities the auxiliary subsystem causes higher environmental load than the solar subsystem, having associated more than 67% of the total emissions per MWh of total thermal energy demand, except for the city of Jaén, where both subsystems produce more balanced environmental load (56% vs 44%).

Within the solar subsystem, the solar collectors' emissions have a weight from 8% (Jaén) to almost 21% (Oviedo); the seasonal tanks between 49% (Oviedo) - 77% (Jaén and Salmanca).

Emissions due to seasonal thermal storage per unit of energy demand are higher in La Coruña than in Oviedo (11.1 % vs 7.6%) despite the fact that the calculated volumes of both tanks are similar, this is due to the fact that the energy demand of Oviedo it is much higher than that of La Coruña, mainly due to the heating demand (2,852.26 vs 1,771.59). The emissions provoked by pumps electricity vary from 10.6% (Jaén) to 26% (Oviedo), while emissions associated to materials (DWH tanks, pumps, heat exchangers and pipes) have a lower percentage: 3.8% (Jaén) – 7.3% (Oviedo).

Oviedo is the city with higher total emissions (169.41 kg of CO_2-eq./MWh of total thermal energy demand) and corresponds to the city with lower solar fraction (< 50%) and almost the smaller seasonal storage; follow by Vitoria, Burgos and La Coruña with emissions higher than 143 kg CO_2-eq./MWh (and solar fraction of 55%, 60.6% and 58.5%, respectively). This is due to the fact that Oviedo, Vitoria and La Coruña are the cities with the least solar radiation, in addition the demand for heating in Burgos is the highest due to its severe winter weather. On the other hand, Jaén has associated lower total emissions (90.85 kg CO_2-eq./MWh) and corresponds to the city with lower thermal and electrical demands, higher solar fraction (88%) and lower surface of solar collector. Barcelona have total emissions below 100 kg CO_2-eq./MWh, (with solar fraction of 76%).

Figure 5 shows the emissions by phase of the LCA and includes the solar fraction (SF%). The relationship between the use of solar energy and the increase in greenhouse gas emissions is shown, mainly in the operation phase. An analysis of this type can help decision-making regarding the implementation of solar fields in places where solar radiation is not very important, marking clear boundaries in some design parameters or complementing solar energy with other types of renewable energy. Clearly it can be deduced by analyzing figure 4 that the solar fraction, which determines the consumption of natural gas, an influential parameter in CO_2 emissions.

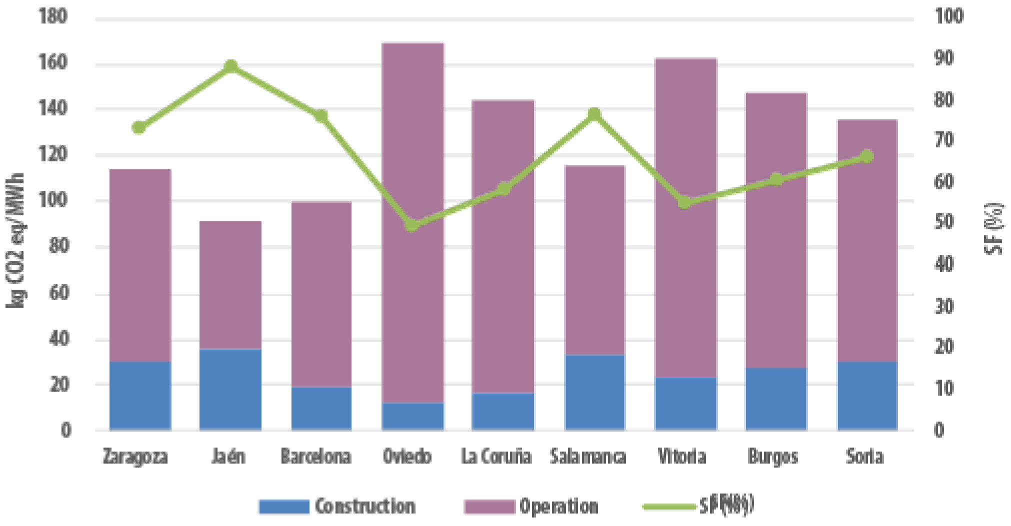

Figure 5. CO_2 emissions per MWh/year and SF (%) for each city.

In the construction phase, seasonal storage is the equipment that generates the highest CO_2 emissions, with the cities of Barcelona, Oviedo and La Coruña being the least impactful. This is due to a design based on Lombohov storage, whose content in cement and steel is less per m^3 of stored water. Furthermore, the reason why emissions are lower for Oviedo and La Coruña than in Barcelona is because the first two have much higher heating demands than the third one.

Regarding the results obtained with the ReCiPe method (Table 11), they present the maximums and minimums for the same cities, although in this case it should be noted that the impacts of the solar subsystem are much more relevant than the impacts obtained by the auxiliary subsystem, reaching in some cases, as in Jaén, the 73%. This is due to the impacts associated to the seasonal storage which are the highest followed by the solar collectors. Figure 6 shows the emissions by phase of the LCA for the ReCiPe method showing the same dependence with the SF that in Figure 5. In colder cities the impacts during the operation phase are greater mainly due to the consumption of natural gas.

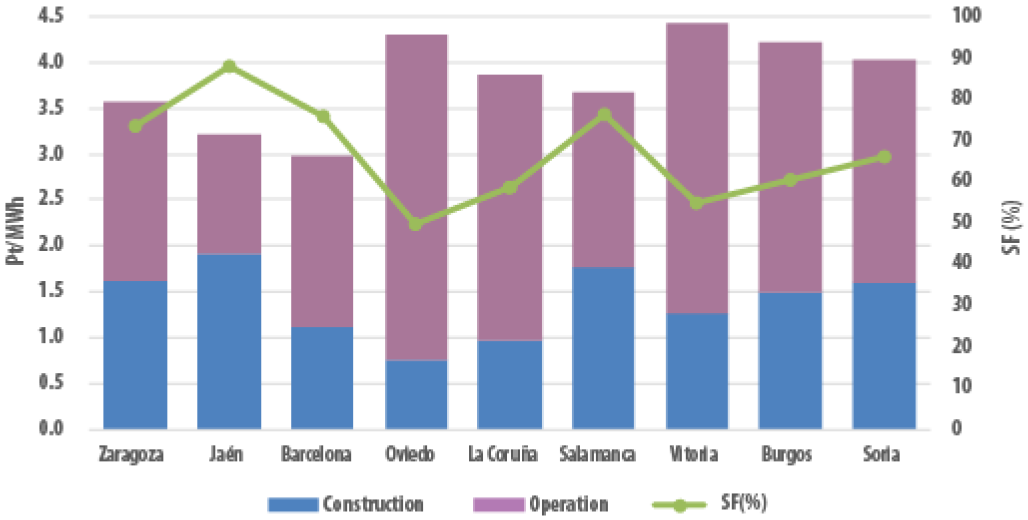

Figure 6. ReCiPe : Pt/ MWh for each city.

The goal of the CED is to calculate the total primary energy input for the generation of a product, then as expected, the natural gas is the product that needs the most energy for its production and distribution (Table 12). Therefore, the CED values for the auxiliary system represent between 60.6% (Jaen) and 87.8% (Oviedo).

4. Conclusions

The LCA of a CSHPSS covering the thermal energy demand for space heating and DHW of 500 dwellings located in Zaragoza (Spain) has been developed. The environmental impacts of solar and auxiliary subsystems have been obtained for three impact assessment methods, namely IPCC (kg of CO_2-equivalent), ReCiPe, and CED, providing a broad evaluation of the environmental burden of different natures provoked by the analyzed system.

The results obtained show that the auxiliary subsystem, despite covering only 26.65% of the heating demand, provokes the highest environmental loads. This is due to the natural gas consumption, which represents in terms of CO_2-eq. emissions 70%, in points of ReCiPe 50%, and in kWh of CED 70%. Nevertheless, the CO_2-eq emissions provoked by the solar subsystem are significant (30%), due to the important amount of materials required for the construction of the seasonal thermal energy storage (75%) as well as to the electricity consumed in the pumps (12%). Solar collectors present a significant lower environmental load (10%).

Therefore, the importance of designing seasonal thermal energy storage systems using techniques and materials with low environmental impact is made clear. Moreover, to a lesser extent, it is recommended that solar collectors use more environmentally friendly materials.

An additional approach has been applied consisting of assigning to the equipment used for heating production their own environmental impacts per MWh of heating demand. The same treatment has been carried out for the equipment involved in the generation of DHW. This allocation of environmental loads leads to the conclusion that the generation system associated with heating is less efficient than the one that produces DHW.

Seasonal storage is revealed as the most polluting equipment. Furthermore, the environmental impacts of different real thermal energy storage tanks from European solar plants have been analyzed. The GHG emissions vary between 3 and almost 15 $kgCO_2$-eq per m^3 of storage volume, the ReCiPe the values obtained vary between 0.16 and 0.6 Pt/m^3 and for CED between 0.01 and 0.07 MWh CED/m^3 depending on the chosen design.

Additionally, the effect of climatic conditions on the design and operation of the CSHPSS has been studied, sizing the plant for different Spanish cities. A plant sizing methodology has been developed based on the parameters obtained in the city under study (Zaragoza). In all cities the auxiliary subsystem causes higher environmental load than the solar subsystem, having associated more than 67% of the total GHG emissions per MWh of total thermal energy demand, except for the city of Jaén (the warmest), where both subsystems produce more balanced environmental load. The ReCiPe points obtained for the auxiliary subsystem vary between 35% for Jaen and almost 80% for Oviedo, while the values obtained from the CED vary between 60% and 87% for the same cities.

The analysis of the relationship between the solar fraction and the increase in greenhouse gas emissions in the operation phase can help decision-making on the implementation of solar fields in places where solar radiation, a priori, is not very high.

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