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Life cycle assessment of an experimental solar HVAC system and a conventional HVAC system

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ABSTRACT

Solar heating ventilating air conditioning systems are useful tools to meet the objectives of the European Commission in terms of sustainability in buildings, since their use can reduce the environmental impact, including CO_2 emissions, due to their low energy consumption. In order to quantify the improvement that in environmental terms the use of this type of system could entail, in this work it was carried out (a) a comparative life cycle assessment of a solar heating ventilating air conditioningsystem based on evaporative cooling and desiccant wheel with a conventional direct expansion system; and (b) an analysis of feasible modifications of the desiccant wheel based system and their influence on the life cycle analysis results. The experimental desiccant wheel based system showed a slightly higher environmental performance than the conventional direct expansion based system, between 2% and 10%, for the 3 impact categories evaluated: human health, ecosystem quality and resource consumption. When weight optimisation and the reuse of materials were considered, the environmental performance of the experimental based system became even up to between 22% and 50% higher than that of the conventional direct expansion based system. That involved a 60 % reduction in climate change potential indicator, which mainly was influenced by CO_2 emissions.

1. Introduction

The growth in energy consumption of buildings has led to more and more problems derived from their associated environmental impacts [1]. The building sector represents 20% [2] and 40% [3] of world and European energy consumption, respectively, together with its consequent CO_2 emissions. Moreover, with the increase in temperature of the earth's surface, the demand for cooling in buildings has abruptly increased [4,5]. Currently, Heating, Ventilating and Air Conditioning (HVAC) systems represent approximately 40% of electrical energy consumption in households, which means 36% of CO_2 emissions. Consequently, European strategies focus on reducing the energy consumption of HVAC systems and their CO_2 emissions [6]. CO_2 is the most abundant greenhouse gas (GHG) on earth followed by CH_4 and N_2O. GHG emission modifies the absorption of thermal radiation in the atmosphere, increasing the greenhouse effect and the temperature of the earth's surface. Therefore, ecosystems and human health are seriously damaged [7].

HVAC systems based on desiccant wheel, DW, are an interesting alternative to refrigeration vapour compression systems [8,9]. Moreover, DW can be integrated into a solar system resulting in a solar-based HVAC system [8]. Solar HVAC systems can highly reduce energy consumption and its associated CO_2 emissions in buildings, contributing to achieve European climate and energy goals. Therefore, the use of fossil fuels and their corresponding environmental impacts associated with the manufacture, use and end-of-life of HVAC systems in buildings may decrease [10–13]. The cooling demand of buildings are higher when more solar irradiation is available; however, solar HVAC technology has so far had few practical applications in recent years, mainly because they are more expensive than traditional HVAC systems, such as the vapour compression system [14]. The solar thermal systems entail an important increase in the cost of the whole solar HVAC system [8]. Nevertheless, the European Union is working on developing new cost-effective strategies to decarbonise the energy system [15] and the solar HVAC systems are a perfect fit for them.

SolarHVAC systems consume mainly energy from renewable sources during operation. However, they also consume energy and resources from non-renewable sources in the other stages of

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Nomenclature

AP	acidification potential.
CEP	carcinogenic effect potential.
CHP	climate change potential.
DEC	desiccant evaporative cooling.
DW	desiccant wheel.
DX	direct expansion.
EC	evaporative cooling.
ETP	ecotoxicity potential.
FFD	fossil fuel depletion.
GFPP	glass fibre reinforce polypropylene.
GFRPs	glass fibre reinforced polymer.
GHG	greenhouse gases.
GWP	global warming potential
HC	heating coil.
HE	heat exchanger.
HVAC	heating, ventilating and air conditioning.
IEC	indirect evaporative cooling.
LCA	life cycle analysis.
LCI	life cycle inventory.
LUP	land used potential.
MND	mineral depletion.
OLD	ozone layer depletion.
PP	polypropylene.
$\dot{Q}$	thermal power [kW]
RDEP	radiation effect potential.
RPEP	respiratory effects potential.
RMSE	root mean standard error.
SCP	single score parameter.
X	temperature or humidity ratio, depending on the case
T	dry bulb temperature [°C]
Th	wet bulb temperature [°C]
V	air flow rate [m^3/h]
ω	humidity ratio [kg/kg]
$\dot{W}$	electric power [kW]

Subscripts

exp	experimental
L	latent
nom	nominal
num	*numerical*
S	sensible
T	temperature
ω	humidity

Superscripts

N	*number of experiments*

their life cycle, manufacturing and end-of-life, thus generating environmental impacts [16]. Therefore, to properly evaluate the real benefits owing to the solar HVAC technologies, their energy life cycle and environmental impacts must be determined [17,18]. A thorough analysis is necessary, considering not only the phases of operation and manufacturing, but its complete life cycle, which means a cradle-to-grave analysis [12].

Life cycle assessment (LCA) is a really useful methodology to carry out a suitable scientific evaluation of any type of product in terms of environmental impacts [19]. The LCA is regulated by the international [20,21] standards and consider energy and raw material consumption, and emissions throughout the whole lifespan of the product [22]. In recent years, several procedures to perform the life cycle impact assessment (LCIA), necessary to perform the complete LCA of a product, has been developed. They range from those that focused on specific aspects such as CO_2 emissions or water footprint to those which involve global assessment. Some of the main LCIA methodologies are: CML2002, Eco-indicator 99, EDIP97 – EDIP2003, EPS 2000, Impact 2002+, LIME, LUCAS, ReCiPe, Swiss Ecoscarcity 07, TRACI and MEEu [23].

Some research has been done in recent years in terms of the life cycle of the building, specifically focused on carbon emissions [24]. The main difficulty in this type of study is the lack of information and the uncertainty of the available data [25]. Prior to LCA, it is necessary to make an estimate of energy consumption during the operation phase, which can introduce some deviations from the real energy consumption [26]. These deviations are especially important in those technologies that consume energy from renewable sources such as solar HVAC systems [24].

When it comes to HVAC systems, specific researches were also performed in terms of LCA. Table 1 summarises the main characteristics of some studies of this type.

Table 1 did not focus on specific data but on general results because LCA methodologies and locations of the involved systems were completely different. Nevertheless, the following useful conclusions were elucidated from Table 1:

- Previous research determined that the operational phase generates the highest energy consumption and environmental damage in traditional HVAC systems, regardless of the environmental indicator analysed or assumption taken [16–18]. This is mainly due to the consumption of electricity from the grid and natural gas. Therefore, the use of the solar HVAC system is really advantageous in terms of environmental performance, because its low energy consumption during the operation phase [11]. However, it is mandatory to increase the lifetime and optimise the equipment design in order to manufacture solar HVAC systems with better environmental performance than conventional HVAC systems [12].
- According to literature, the environmental impact generated by solar HVAC systems is mainly due to their manufacture and end-of-life phases [11,12,22]. Furthermore, geographic area also strongly affects environmental performance. A particular solar HVAC system may present a lower environmental performance than a conventional HVAC system in one specific location and higher in another. Therefore, the comparison must be conducted in the same geographic area [10,16,17].

In addition, some authors proposed mathematical methods based on eco-design techniques in order to optimise the solar HVAC system design and consequently minimise the energy consumption and environmental footprint [27].

The eco-design is a methodology consisting of a set of strategies that can help to reduce the impact of manufacturing a product, especially related to renewable systems [12]. Actually, eco-design fundamentals ought to be implemented in the design of all types of products [28]. Material selection is a crucial task to design a product according to eco-design guidelines. For instance, the use of aluminium in those components where low weight is not critical, it is not the best option. That is because energy-efficient metals, such as steel, can replace energy-intensive metals such as aluminium [29].

Moreover, when steel is compared to glass fibre reinforced polymers (GFRPs), the latter show lower energy consumption

Table 1
Review of research performed in terms of LCA of HVAC systems.

Study	Reference system	LCA Method	Location	Life phases impact on the SHS	SHS vs CS
[22]	DEC system powered by a photovoltaic/thermal air collector	ILCD 2011 Midpoint method	Palermo, Italy	MS represent more than 70%, e.g. 75% for GWP	No data
[12]	Small-size SHS based on adsorption cooling and CPC solar collectors	LCA tool developed in the International Energy Agency SHC, Task 48	Barcelona	MS represent 50% of GWP	SHS has better performance by increasing lifespan. MS represent 15% of GWP in CS
[18]	Evaporative cooling system with desiccant materials and photovoltaic/thermal solar system	ILCD 2011 Midpoint method	Palermo, Italy	MS represent more than 75% in almost all indicator. E.g. 74% of GWP	SHC has less impact, up to 50% lower than CS in some indicators. MP represent 6.8% of GWP in CS
[10]	SHC composed of absorption chiller, solar collectors, gas boiler and conventional chiller	International Energy Agency SHC Task 48	Palermo (Italy) and Zurich (Switzerland)	Operation phase is responsible for about 60–97% of all impacts	No data
[14]	SHS based on parabolic solar concentrators and an absorption system	Carbon footprint based on the 100-year global warming potential	California	No data	The SHS reduce the carbon footprint up to 70% compared to CS
[11]	SHS based on absorption	CML 2baseline 2000	Bangkok, Thailand	Impact saving in the use phase, overweighed the high impact in the non-use phase	Global impacts of the SHS were reduced 26–40% compared to CS

MP: Manufacturing phase; Solar HVAC system: SHS; Conventional system: CS

and lower GHG emissions in the manufacturing phase [30]. A cradle-to-grave analysis for an I-beam (beam with the shape of I) made of steel versus the same I-beam made of GFRP was conducted [31]. Result elucidated 20 % less environmental impact when GFRP was selected as material. GFRPs are currently considered one of the most practical fibre reinforced polymers (FRPs), due to its low weight, low cost, and high mechanical resistance. Therefore, GFRPs are used in several products such as printed circuit boards, tanks and pipes, car body panels, and wind turbine blades [30].

In summary, most LCAs conducted on traditional or renewable HVAC system analyse at least one of the following topics. In our case, the last two topics have been analysed:

- Effect of system location on environmental performance.
- Effect of facility size on environmental performance.
- Optimal sizing for minimal environmental impact.
- Determination of those phases of the system life cycle with the greatest impact.
- Comparison of conventional systems with innovative systems, such as solar HVAC systems, in terms of environmental impact.

It is remarkable that no work was found on eco-design strategies focused on recyclability or reuse strategies for solar HVAC systems. Considering the environmental impact generated by solar HVAC systems is mainly due to their manufacture and end-of-life phases, reuse or recyclability can be especially advantageous in solar HVAC systems in terms of circular economy and sustainability.

This work had two main targets: (a) to perform an LCA on a solar hybrid HVAC system based on a DW, an indirect evaporative cooler (IEC) and a thermal solar system and compare it with a commercial HVAC system based on DX; (b) to evaluate the improvements of the DW-based system after applying eco-design strategies, focused on weight reduction, material changes and reusing materials at the end-of-life of the system.

2. System description

The experimental installation was located in Andaltec (Martos, southern Spain). The prototype installation consisted of a DW-based system and a solar field, specifically designed to supply the air conditioned to a 63.8 m^3 research lab room with controlled temperature and humidity. Following are described the DW-based system, the facilities, and the DX-based system, used to make the LCA comparison.

2.1. DW-based system

The DW-based system (Fig. 1) was mainly composed of a DW, evaporative cooling (EC) system, heat exchanger (HE), heating coil (HC), and a small hydraulic pump to move water around the EC. The EC together with the HE constituted an IEC. Furthermore, fans were installed to supply a flow rate of up to 1600 m^3/h and filter to clean the air.

Three different airflows operated in the DW-based system in order to handle air from the system (Fig. 1). The process airflow driven by fan 1 passed through the DW to control the supply humidity ratio, and then it was treated by the HE and the HC to adjust the supply temperature. Regarding the regenerative airflow driven by fan 2, it was used to regenerate the DW. This regenerative air flow was heated by means of a HC, which was fed with hot water from the solar system. The cooling airflow driven by fan 3 was used to cool the process air flow in the HE, this airflow was previously cooled by an EC. The main technical characteristics of the DW-based system are shown in Table 2. Additionally, Comino *et al.* [6] described more detailed information about this facility.

2.2. DX-based system

A conventional DX-based system was selected as a reference to compare the prototype DW-based system. This HVAC system was designed to control air temperature and air humidity in a room, just what the DW-based system was capable of as well.

The commercial DX-based system was mainly composed of a direct expansion unit to cool and dehumidify air. Additionally, a HC powered by a solar thermal system was installed to generate hot water, generally required during the cold season. The same solar thermal field and HC were connected in both systems. The DX-based system used three centrifugal fans for each of the three airflows showed in Fig. 2. The technical characteristics of the DX-based system are shown in Table 3.

2.3. Facility location and description

A scheme of the installation setup is presented in Fig. 3. In addition to the main components of the facility, secondary elements such as water storage tank, control valves, 3-way valve, filter,

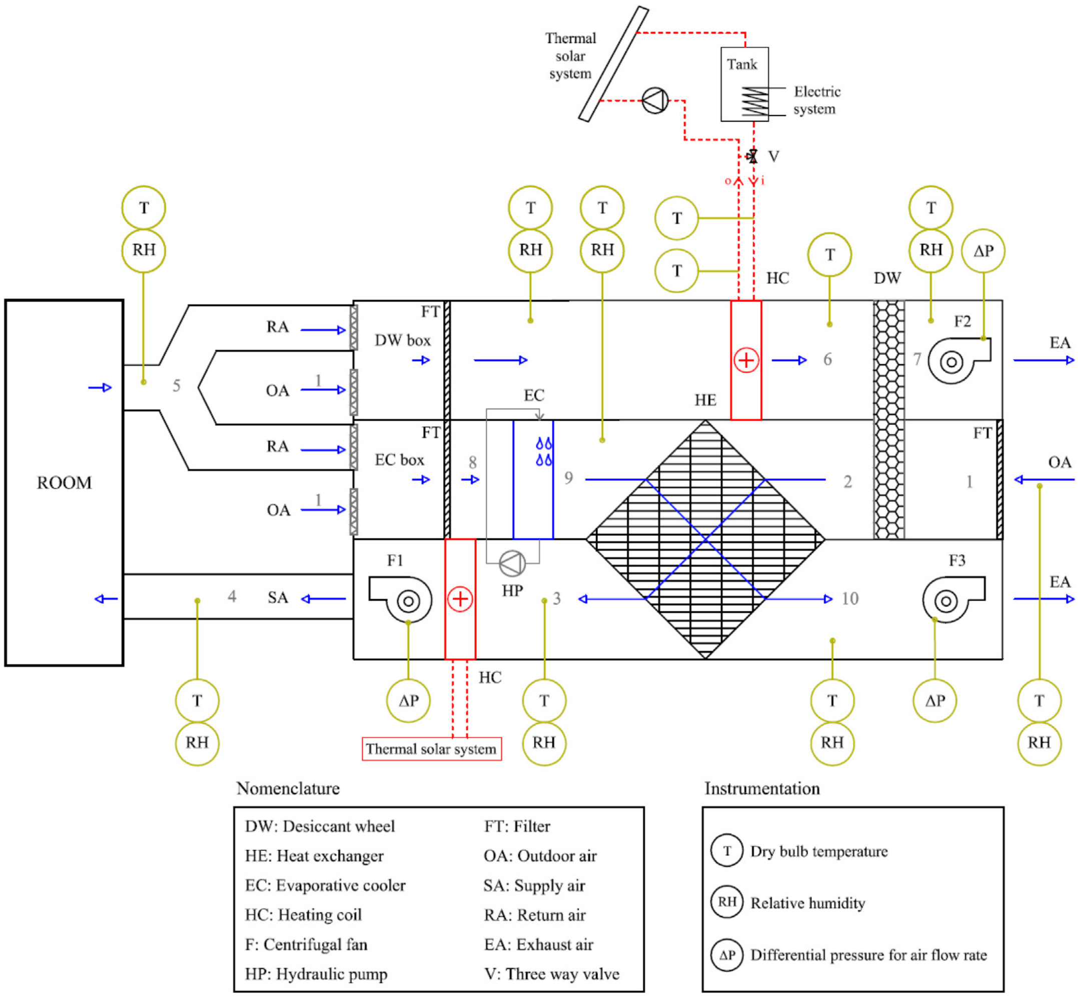

Fig. 1. Scheme of the DW-based system (obtained from Comino et al. [6]).

flowmeter, pressure relief valve, electric pump and purge system are also presented. The water storage tank had an electrical support to generate heat when the solar radiation was not enough to collect the required energy. Regarding the secondary elements, all of them were made of copper covered with thermal insulators and joined by means of brass welding.

The solar field presented in Fig. 3 was composed of 12 collectors. Each collector was constituted of one thermal solar field structure made of aluminium, 15 parabolic channels made of polymer-based material to concentrate the solar energy, and 15 vacuum tubes aimed to absorb the solar energy and avoid thermal losses. The entire solar field can supply a power of 7 kW when the maximum demand for cooling was reached (generally in the afternoon) without any solar tracking. Therefore, the parabolic channels were oriented at a specific angle (15°) in order to give the maximum power in the afternoon.

Moreover, the entire facility was monitored through humidity and temperature sensors in order to obtain the necessary data to determine the effectiveness of the whole system, as well as the effectiveness of each component separately. Comino *et al.* [6] provided a more detailed description of the facility.

3. System performance modelling

Annual energy simulations were carried out with the assumption that both HVAC systems served a research lab room. The energy simulations were carried out with the TRNSYS 17 software [32], using a time step of 5 min. The simulations were performed for the climatic conditions of Martos (southern Spain). The mathematical models used in the energy simulations are summarised in Table 4. The components that compose both HVAC systems were modelled as described below. The desiccant wheel and the direct expansion unit were modelled from experimental tests, see Eqs. (1) and (2) and Eqs. (3) to (5), respectively. The subscripts of these equations are the same as shown in Fig. 1. Models included in the TRNSYS library (Types) were used for the rest of the HVAC components, since they are commonly studied components.

The calibration of the two HVAC systems, the DX-based system and the DW-based system, was carried out using the temperature and humidity ratio data collected during the experimental campaign, see Fig. 4 and Fig. 5. Experimental data collected during a period of 8 weeks from different seasons of the year were used for the calibration of the mathematical models. The models were calibrated under the real climatic condition of Martos (southern Spain). Both HVAC systems were designed to independently control the temperature and humidity ratio of the room air, as described in section 2. It can be observed that R^2 values equal or higher than 0.96 were obtained for the models, see Fig. 4 and Fig. 5. The root mean standard error, RMSE, was also obtained for the comparison of the experimental and numerical results, see Table 5, $RMSE_T$ for temperature and $RMSE_\omega$ for humidity ratio. It was calculated by Eq. (6), where $X_{i,exp}$ was the measured value and $X_{i,num}$ was the numerical value. These results of RMSE are in agreement with those obtained in previous research works. Martí-

Table 2
Technical characteristics of the main components of the DW-based system.

FAN	
Airflow rate (m3/h)	500 – 3000
Power (W)	400
Main materials	Steel, copper and polypropylene (PP)
Weight (kg)	38.7
DW	
Nominal airflow rate (m^3/h)	2000
Nominal desiccant capacity (kg/h)	10
Main materials	Silica gel, glass fibre and acrylic
Peso (kg)	5.1
HE	
Nominal airflow rate (m^3/h)	3300
Working temperature range (°C)	−30 to +90
Main materials	Steel and aluminium
Weight (kg)	35.2
EC	
Evaporated water (l/min)	0.04
Main materials	Glass fibre, steel and PP
Weight (kg)	28.5
HC	
Main materials	Copper and aluminium
Weight (kg)	29.7
PROTOTYPE AIR CONDITIONING SYSTEM STRUCTURE	
Main materials	Steel and thermal insulator
Weight (kg)	312.8
SOLAR FIELD	
Main materials	Aluminium, polycarbonate, copper, glass.
Weight of each collector (kg)	55
Maximum power (kW)	7

nez, P.J. et al. [33] obtained $RMSE_T$ values between 0.29 °C and 0.94 °C and $RMSE_\omega$ values of 0.47 g/kg. Angrisani, G. et al. [34] obtained values of $RMSE_T$ and $RMSE_\omega$ of up to 1.28 °C and 0.3 g/kg, respectively.

$$T_2 = e^{(}2.4144 + 0.0234\text{Â}\cdot T_1 - 0.005\text{Â}\cdot \omega_1 + 0.0096\text{Â}\cdot T_6 + 0.0057\text{Â}\cdot \omega_6) \quad (1)$$

$$\omega_2 = e^{(}1.142 + 0.0042\text{Â}\cdot T_1 + 0.0562\text{Â}\cdot \omega_1 - 0.0030\text{Â}\cdot T_6 + 0.0518\text{Â}\cdot \omega_6) \quad (2)$$

$$\dot{Q}_S = \dot{Q}_{S,nom}\text{Â}\cdot (0.0792\text{Â}\cdot T_1\text{Â}\cdot V + 0.0021\text{Â}\cdot T_1\text{Â}\cdot Th_1 - 0.076\text{Â}\cdot Th_1\text{Â}\cdot V - 0.002\text{Â}\cdot Th_1^2 - 0.001\text{Â}\cdot T_1^2 - 0.133\text{Â}\cdot V^2 - 0.035\text{Â}\cdot Th_1 + 0.292\text{Â}\cdot V + 0.029\text{Â}\cdot T_1 + 0.489) \quad (3)$$

$$\dot{Q}_L = \dot{Q}_{L,nom}\text{Â}\cdot (-0.111\text{Â}\cdot T_1\text{Â}\cdot V - 0.005\text{Â}\cdot T_1\text{Â}\cdot Th_1 + 0.132\text{Â}\cdot Th_1\text{Â}\cdot V + 0.002\text{Â}\cdot Th_1^2 + 0.002\text{Â}\cdot T_1^2 - 0.331\text{Â}\cdot V^2 + 0.112\text{Â}\cdot Th_1 + 0.532\text{Â}\cdot V - 0.047\text{Â}\cdot T_1 - 0.145) \quad (4)$$

$$\dot{W} = \dot{W}_{nom}\text{Â}\cdot (0.003\text{Â}\cdot T_1\text{Â}\cdot V + -0.001\text{Â}\cdot T_1\text{Â}\cdot Th_1 - 0.030\text{Â}\cdot Th_1\text{Â}\cdot V + 0.001\text{Â}\cdot Th_1^2 + 0.001\text{Â}\cdot T_1^2 + 0.347\text{Â}\cdot V^2 + 0.029\text{Â}\cdot Th_1 - 0.338\text{Â}\cdot V - 0.003\text{Â}\cdot T_1 + 0.603) \quad (5)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(X_{i,exp} - X_{i,num}\right)^2}{N}} \quad (6)$$

4. LCA methodology

LCA is a widely used methodology to study deeply the environmental impact of products, through all its life cycle phases, from row material extraction, to the end-of-life of the products. LCA can be conducted by means of 4 principal phases: (a) goal and scope definition, (b) inventory analysis, (c) impact assessment, and (d) results interpretation [20].

4.1. Scope and goal definition

The methodology followed in the present work is detailed in Fig. 6. Firstly, the scope and objective were defined, and thus, the functional unit. In this case, the functional unit was defined as the air conditioning of a 25.5 m^2 room for a period of 25 years, where 25.5 m^2 is the area that each system handles and 25 years, the systems lifespan. Secondly, the information regarding consumption of raw material and energy consumption during the operation phase was gathered in the inventory analysis. Thirdly, the impact assessment was performed by means of Ecoinvent 2017 database [35] and Eco-indicator 99 methodology [23]. Finally, the results obtained from first and second objective were studied and a sensitivity analysis was also performed.

A summary of the case studies analysed is shown in Table 6. Firstly, a comparative LCA between the DW-based system and the DX-based system described previously was carried out. Furthermore, in this first analysis the weak point of both systems was determined.

Secondly, three cases (DW2, DW3 and DW4) for the DW-based system were investigated in order to minimise the weak point, by means of eco-design and circular economy basis. The improvements were focused on the manufacturing phase by means of a design enhancement (DW2) and on the end-of-life phase by means of material reusing (DW3). These potential improvements were defined after determining the weak point for DW-based system (DW1).

The improvements focused on the component with the greatest weight, the solar field, and the prototype air conditioning system structure. This structure weighed 312.8 kg and was made primarily of steel and aluminium. Each collector of the solar field weighed 55 kg and was made mainly of aluminium (the whole thermal solar field structure), polycarbonate, copper and glass.

A design optimisation based on eco-design techniques was investigated in DW2. More specifically, it was studied the replacement of the steel that composed the prototype air conditioning system structure of the DW-based system (Fig. 7) by glass fibre reinforce polypropylene (GFPP). A weight reduction of more than 50% can be achieved by replacing steel with GFRP material [36], therefore a 50 % of weight reduction was considered as a result of apply eco-design methodology.

Furthermore, in DW2 the thermal solar field structure (Fig. 8) was also considered for promising enhancements. In this case, the improvement consisted of changing the original material, aluminium, by steel. This change was proposed because of aluminium present higher environmental impact than steel in the manufacturing phase owing to the high amount of energy necessary to convert bauxite into aluminium [29]. Steel is tougher than aluminium, however it is three times as heavy, which means that stronger structures with less weight can be made by using aluminium [37]. Nevertheless, this structure presents potential margin for improvement in terms of weight reduction, and prior to industrialisation, a weight optimisation could achieve this material change without any weight increase, just reducing the current wall thickness.

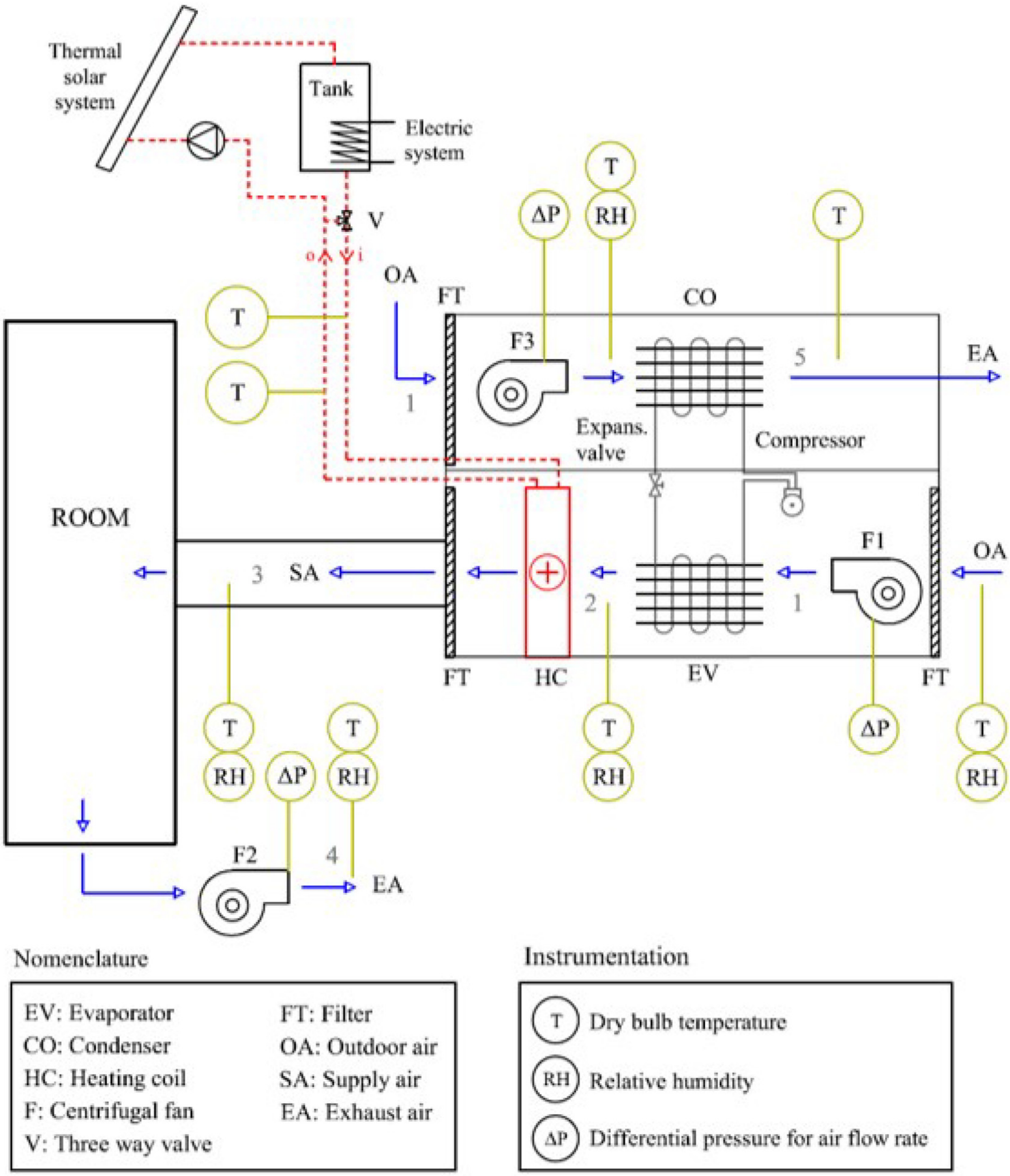

Fig. 2. Scheme of the commercial DX-based system.

As for costs, steel raw material is about three times cheaper than aluminium. Moreover, in terms of part manufacturing costs, aluminium is around 45% more expensive than steel [38]. On the other hand, GFRPs provide notable cost reduction in comparison with steel, up to 50% cost reduction [39]. Therefore, in the present work the substitution of aluminium by steel in the thermal solar field structure and steel by GFRP in the prototype air conditioning system structure could additionally provide a significant cost reduction for the DW-based system.

Regarding the reuse of material studied in DW3, a specific reuse of the main materials involved was investigated due to the fact that reusing is presented nowadays as an interesting alternative to improve the environmental performance [40]. It is remarkable that there is not too much information in bibliography regarding the reuse of material from HVAC systems, which prompts to study this reusing strategy.

For the case study DW3, a mechanical design based on the modularisation strategy proposed by Kimura *et al.* [41] was developed. A modularised product make simplifies the disassembly process, and so, increasing the potential reuse of industrial products after the lifespan [41]. The modularisation would be focus on thermal solar field structure and prototype air conditioning system structure, allowing to disassembly these two structures quickly and easily. Approximately 50% of steel and aluminium used in industrial products could be reused [42], therefore the reuse of 50% of steel and aluminium consumed in the DW-based system were investigated in DW3.

For DW4, the two improvements analysed in cases DW2 and DW3 were investigated together, in order to study the synergic effect of these improvements working together.

Finally, DW5 was proposed in order to study the sensitivity of the results regarding power consumption in the operational phase. The

Table 3
Technical characteristics of the main components of the DX-based system.

FAN	
Airflow rate (m3/h)	500 – 3000
Power (W)	400
Main materials	Steel, copper and PP
Weight (kg)	38.7
WATER CONDENSER	
Nominal power (kW)	6.6
Nominal water flow (m^3/h)	1.2
Main materials	Aluminium, steel, coolant R407c and copper
Weight (kg)	24.7
COMPRESOR	
Main materials	Steel, copper, plastic and oil
Weight (kg)	30.60
WATER EVAPORATOR	
Main material	Copper and aluminium
STRUCTURE OF THE DX-BASED SYSTEM	
Main materials	Steel and thermal insulator
Weight (kg)	113.5
SOLAR FIELD	
Main materials	Aluminium, polycarbonate, copper, glass.
Weight of each collector (kg)	55
Total power (kW)	7
HC	
Main materials	Copper and aluminium
Weight (kg)	29.7

sensitivity analysis attempt to investigate how LCA results were affected by the uncertainties in the data used, hypotheses or simplifications, calculation procedures, etc. A 10% more electricity consumption from the electricity grid in the operational phase was investigated for the DW based system in order to carry out DW5.

It is noteworthy that DW1 always ensured 100% treated outside air, meanwhile DX1 usually ensured 30–40% treated outside air. That means the indoor air quality supply by DX1 was lower than the indoor air quality supply by DW1. The indoor air quality parameter was not taken into account in the LCA because of the assessment method criteria does not allow that, nevertheless it was undoubtedly an advantageous quality for the DW1 to take into account.

4.2. Inventory analysis

The inventory analysis determines and quantifies the consumption of energy, water and other raw materials, as well as environmental emissions. In general, the inventory presented in this work focused on critical aspects that generate significant environmental impacts in the systems analysed. Inventory analysis can be divided into the 3 main stages of the life of a product: manufacturing, operation and end-of-life.

In the manufacturing phase, the consumption of raw material was taken into account for each subcomponent of the systems (Table 2 and 3), using the Ecoinvent 2017 database [35]. The inventory did not include electronics and automation subcomponents or similar parts due to lack of data. Energy consumption during the manufacture of the raw material and assembly was considered by means of Ecoinvent 2017 [35]. Transportation and installation of each system were not taken into account because its environmental impact was not representative in comparison with the total environmental impact [12].

In the operation phase, the calculation of energy consumption presented above was taken into account. The calculation concluded that the energy consumption in the whole products life was 26775.00 and 31046.25 kW for the HVAC solar system and for the conventional system, respectively. It was taken into account, a surface area to be air-conditioned of 25.5 m^2, a useful life of 25 years, and a working period from 9:00 a.m. to 4:00p.m. and from Monday to Friday. The useful life of the main components was established at 25 years without the need for replacement (data provided by the manufacturers). During operation, refrigerant losses were estimated to be around 6% of the total refrigerant charge of the DX system [43]. Regarding additional maintenance, such as filter replacement and similar operations, it was not considered because its environmental impact is almost negligible [12].

Finally, in the end-of-life phase, landfill disposal was considered for all cases in which reuse was not taken in account. As explained above, for those cases where reuse is included, 50% aluminium and steel from the DW-based system were considered as reusable material. Regarding the dismantling of the system, it was not considered because manual disassembly was proposed for the end-of-life of the products. Furthermore, the disposal scenario for both systems took into consideration the dumping of any non-recyclable material, such as refrigerants, and the disposal of all hazardous waste in suitable facilities.

4.3. Life cycle impact assessment (LCIA)

For this work, Eco-Indicator 99 method was selected due to its ease to perform comparison of results. This method assesses the

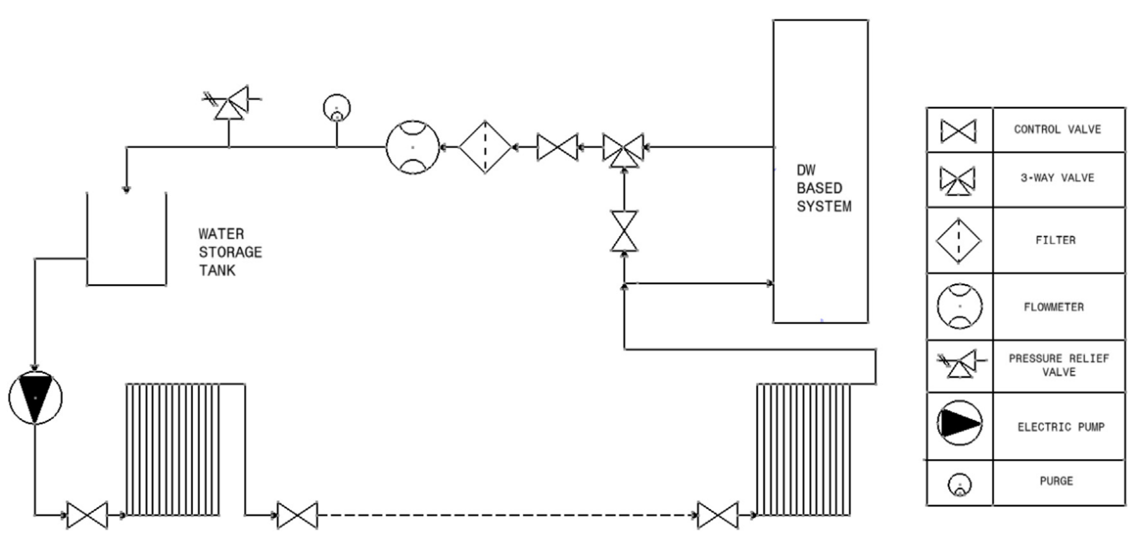

Fig. 3. Scheme of the thermal solar installation.

Table 4
Mathematical models of HVAC components.

Components		Models
Hybrid HVAC system		
	Desiccant wheel	Eq. (1) and (2)
	Heat exchanger	Type 5e
	Evaporative cooler	Type 506c
	Heating coils	Type 754
	Centrifugal fans	Type 111a
Conventional HVAC system		
	Direct expansion unit	Eqs. (3), (4) and (5)
	Heating coil	Type 754
	Centrifugal fans	Type 111a

life cycle based on the three impact categories described below [23]:

- Impacts on natural resources: assesses the damage produced by the extraction of mineral resources and fossil fuels. This category is represented by the Land Used Potential (LUP) indicator.
- Impacts on quality of ecosystems: assesses the species that have disappeared in a certain area. This category is represented by Mineral Depletion (MND) and Fossil Fuel Depletion (FFD) indicators.
- Impacts on human health: assesses the damage to human health. This category is represented by the following indicators: Carcinogenic Effect Potential (CEP), Respiratory Effects Potential (RPEP), Climate Change Potential (CHP), Radiation Effect Potential (RDEP), Ozone Layer Depletion (OLD), Ecotoxicity Potential (ETP) and Acidification Potential (AP).

All the previously described impact categories can be gathered in only one parameter, named “single score parameter” (SCP). Different criteria can be applied in order to calculate this parameter, in our case hierarchical perspective was applied, in this perspective quality of ecosystem and human health represent each one 40% of the SCP and natural resources the remaining 20%. It is not mandatory, or even recommended, to summarised all impact categories in one single parameter when the comparison is to be showed to the public [21]. Therefore, due to this work is intended to be public, the SCP was used briefly. It will only be used for the purpose of showing the critical design points, and then, justify the improvement proposed for the DW based system. In this sense, SCP was proposed due to it gives us a clearer understanding regarding the environmental impact generated by each component.

5. Results

5.1. Comparative analysis of DW1 and DX1

A comparative study between the cases studies DW1 and DX1 was carried out. The results obtained of this study are shown in Fig. 9. The percentage change in environmental performance (PC_{EP}) for Case DW1 and DX1, taken as reference DX1, was represented in this figure. PC_{EP} was evaluated on the following indicator: CEP, RPEP, CHP, RDEP, OLD, ETP, AP, LUP, MND and FFD. In Fig. 9, and generally in all figures where PC_{EP} appears, PC_{EP} was calculated as a percentage change from the DX1 system, always considering DX1 as a reference for this measure.

DW1 consumed higher amount of material during the manufacturing phase than DX1 due to the steel requested for the prototype air conditioning system structure. Therefore the high amount of metal used in DW1 explains the higher values of FFP, OLD, LUP, CEP and RPEP indicators for DW1, despite the fact that steel has a low impact per weight unit, owing to the power consumption during the manufacture process is not excessively high [29].

The values of ETP and MND for DX1 were higher than those for DW1, see Fig. 9. This is due to the fact that DX1 presented a higher consumption of both, copper and energy than DW1 in the operation phase. Copper generates major contributions on ETP because copper consumption has a direct effect on water resources [7]. Moreover, MND was also highly influenced by copper consumption [43]. Regarding RDEP, the greatest impact was related to the use of nuclear energy for the generation of electricity in Spain, and so, the emissions of radioactive particles during uranium mining [43]. Therefore, the AP, ETP, RDE, MND and CHP indicators were higher for DX1 than those for DW1. Furthermore, it is remarkable that CHP indicator, which evaluates the CO_2 emissions, was around a 30% lower in DW1 than that in DX1.

The three impact categories described in section 4.3 were represented in Fig. 10 for DW1 and DX1, in order to obtain a general conclusion. It is notable that DW1 generates a lower impact in all categories, between 2% and 10% less than DX1. The highest difference was observed in the human health category, mainly due to its dependence on CHP indicator, whose value for DW1differs significantly from DX1 (Fig. 9).

The SCP values of each material of DW1 at the manufacturing phase are shown in Fig. 11. It can be observed than aluminium primarily belongs to the thermal solar field structure, and steel to the prototype air conditioning system structure. It is also remarkable that even though the amount of copper was much lower than the amount of steel and aluminium, the SCP achieved by cooper was not too far from aluminium and steel. This phenomenon was

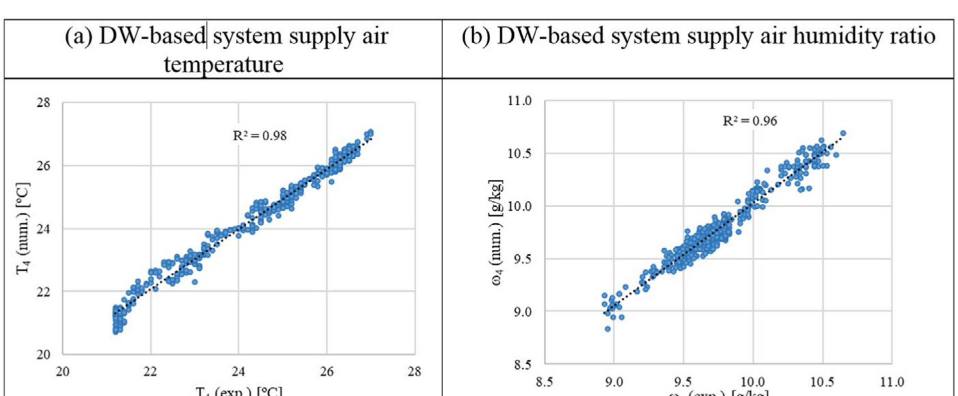

Fig. 4. Calibration of the models of the DW-based system.

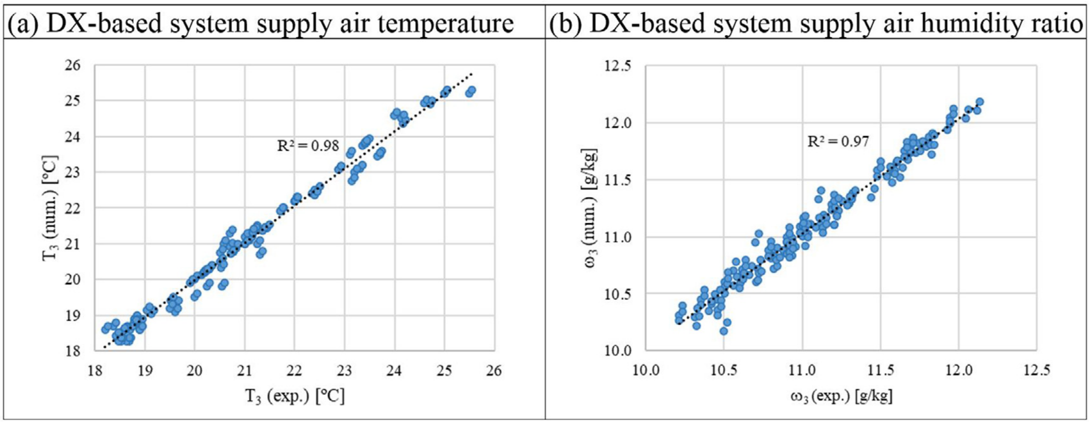

Fig. 5. Calibration of models of the commercial DX-based system.

Table 5
RMSE values for the HVAC models.

Variable	$RMSE_T$ [°C]	$RMSE_\omega$ [g/kg]
DW-based system		
T_4	0.237	–
ω_4	–	0.108
DX-based system		
T_3	0.262	–
ω_3	–	0.154

explained because of the significant amounts of Hg, Cr, As, Pb and CN generated during copper [44].

The SCP values of each material of DX1 are represented also in Fig. 11. Similarly, for DW1, aluminium shows the highest value. Regarding refrigerant and oil, even though both have a really high environmental impact per weight unit [7], the overall impact of them was negligible in DX1. It was due to the percentage of them in relation with the total amount of involved materials was not really significant.

Fig. 12 presents the three global impact categories for DW1 and DX1. The bars show the impact percentage due to the operational phase, the manufacture phase and the end-of-life phase.

The environment impact in DW1 owing to manufacturing phase was between 70% and 90% of the total impact. The impact caused by the operational phase, which mainly depends on consumption of electrical energy from the grid, was between 5% and 20% and finally, the impact due to end-of-life phase was between 5 and 10% (Fig. 12). Regarding DX1, results were significantly different, due to the higher electrical consumption during the operational phase. This fact generated an increase of the impact due to the operational phase from 5 to 10% up to 20–40% of the total impact. Therefore, the environment impact owing to manufacturing phase was reduced from 70% to 90% to 60%-70%. Regarding end-of-life phase impact, the result for DW1 is similar to that of DX1.

It is possible to conclude that if the lifetime were increased in both cases, the advantage for DW1 would be greater than for DX1, in terms of environmental impact. The impact due to the manufacturing phase and the end-of-life would be the same, but the impact due to the operation phase would be directly proportional to the lifetime. Therefore, owing to the operational phase in DW1 is lower than in DX1, the increase in the environmental impact in DX1 would be greater than in DW1. That means, it could be possible to improve the environmental performance (regarding all indicator studies in this work) for the DW based system by increasing the lifespan. It was due to the environmental benefits associated with the use of a renewable system during operation counterbalances the additional impact generated during the rest of stages of its life cycle [12].

5.2. Influence of optimisation on environmental impact for the DW based system

According to the previous results obtained from the evaluation of DW1 and DX1, the materials used in the prototype air conditioning system structure and the thermal solar field structure present a much greater impact than the other materials used in the facility. Therefore, the following proposed improvements were focused on reducing the amount of material (mainly steel and aluminium)

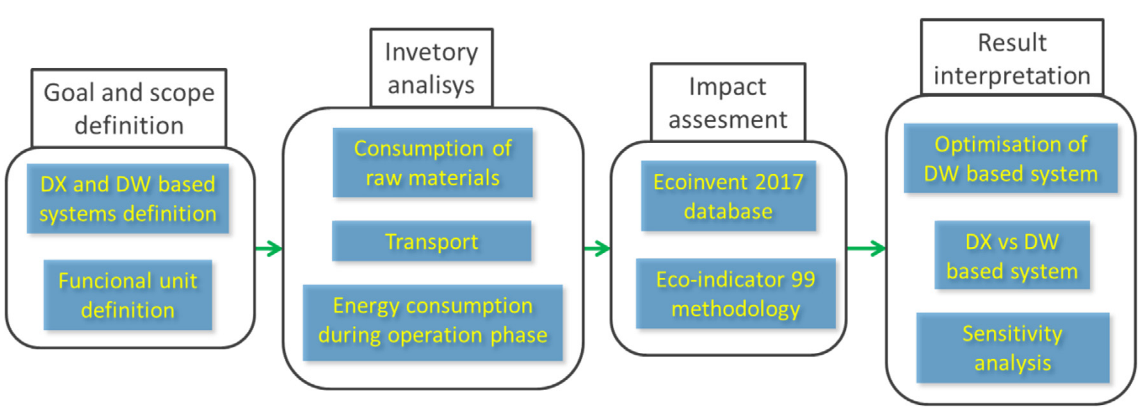

Fig. 6. Work methodology.

Table 6
Study cases proposed.

DW1	DW-based system
DX1	DX-based system
DW2	DW-based system with a design optimization
DW3	DW-based system with improvements in the end-of-life stage
DW4	DW-based system with improvements in the manufacturing and in the end-of-life stage
DW5	Influence of electrical consumption from grid. DW-based system with 10% more electricity consumption.

Fig. 7. Prototype air conditioning system structure.

Fig. 8. Thermal solar field structure.

consumed in the manufacturing step for these structures. More specifically, it was proposed two types of improvements. The first one was a design optimization of both, the prototype air conditioning system structure and the thermal solar field structure by means of using eco-design fundamentals like weight reduction and using more environmentally friendly material (DW2). The second was an enhancement of the end-of-life stage by means of materials reusing, specifically the reuse of the 50 % of the materials involved in the facility was investigated (DW3). Finally, the two proposed improvements working together were analysed to in DW4.

5.2.1. Design optimisation (DW2)

It was considered the substitution of the original material, steel, that constituted the prototype air conditioning system structure (Fig. 7) by GFPP. Additionally, the thermal solar field structure (Fig. 8) was also considered for potential improvements. In this case, the enhancement consisted in changing the original material, aluminium, by steel.

Fig. 13 summaries the contribution of the manufacture phase to the SCP in DW1 and DW2, respectively. The maximum value obtained in DW1 (2700 for aluminium) was almost twice the maximum value in DW2 (1400 for steel). It was due to the amount of aluminium involved in DW1 was more than double that of DW2 as consequence of the design improvements proposed. Therefore, after the enhancement, aluminium reaches the second higher score (1100) and copper the third one (900).

A comparison between DW1 and DW2 indicators was presented in Fig. 14, specifically CEP, RPEP, CHP, RDEP, OLD, ETP, AP, LUP, MND and FFD indicators were analysed. It shows a reduction on all indicators for DW2.

In Fig. 14, it can be observed than DW2 presents lower values for all indicators owing to the lower material consumption during the manufacturing phase and the use of more environmentally friendly materials. The most affected indicator in DW2 were CEP, RPEP, CHP and OLD. Regarding CHP, in DW2 was achieved a 20% more reduction than in DW1, with respect to the reference case, DX1 (Fig. 14). It was especially remarkable owing to this parameter affect directly to the global warming. These results were mainly explained because of the reduction on aluminium consumption in the manufacture phase. As it was explained previously, a high amount of energy is necessary to turn bauxite into aluminium, therefore aluminium is a non-environmentally friendly material in some applications [29]. Regarding ETP, RDEP, AP, LUP, MND and FFD DW2 presents less significant variations. It was justified basically due to the increase in GFRP consumption and the amount

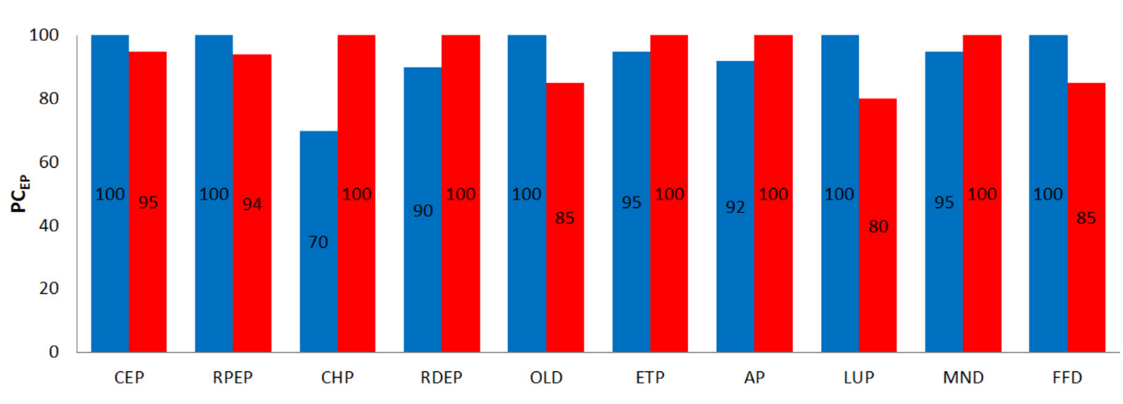

Fig. 9. Environmental Impact indicator comparison for DW1 vs DX1.

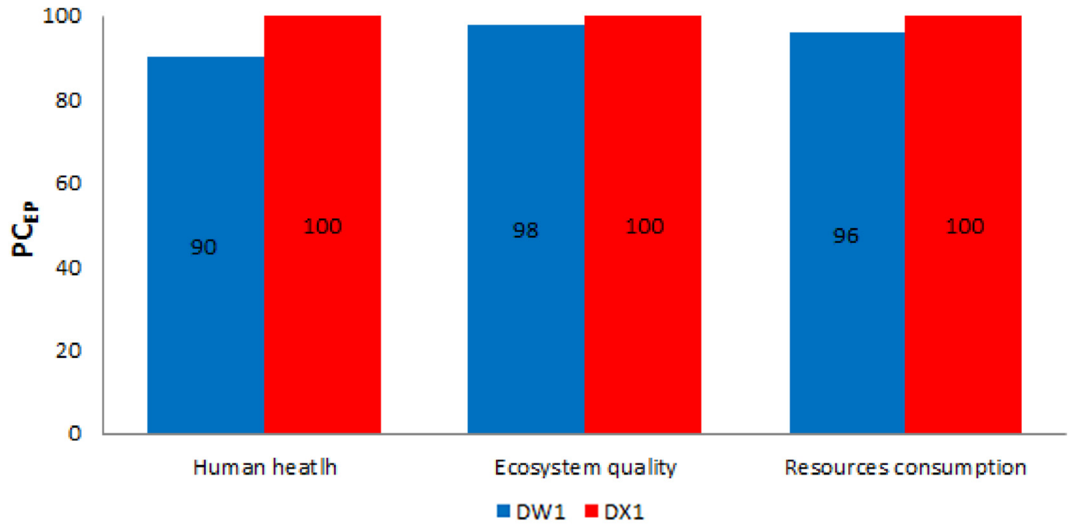

Fig. 10. Impact categories comparison for DW1 vs DX1.

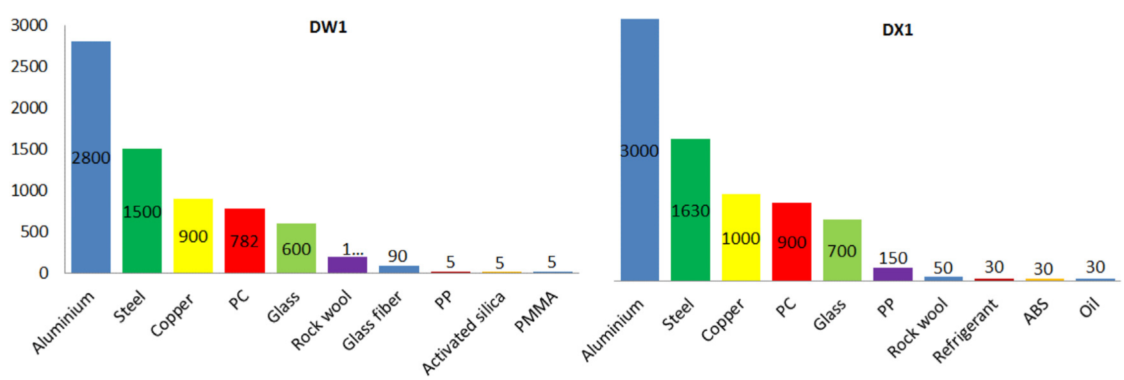

Fig. 11. SCP generate by each material at the manufacturing phase of DW1 on the left and of DX1 on the right.

of steel and copper in DW2while no change in that occurs in DW1. ETP was highly influenced by copper [7] and by MND [43].

The three impact categories for DW1 and DW2 are represented in Fig. 15. The results are in agreement with Fig. 14 and showed that the impact reduction achieved in DW1 was greater than that in DW2: 30% greater for human health, 5% for ecosystem quality and 20% for resources consumption. This fact was due to the reduction on the raw material consumption (aluminium), which counterbalances the addition of GFRP, resulting in a positive effect on all impact categories studied.

5.2.2. Material and components reuse (DW3)

According to the previous results aluminium and steel present the most significant contribution to the value of SCP (Fig. 11). Consequently, these materials were selected to conduct the reusing strategy investigated in DW3.

A comparison between DW1 and DW3 indicators is presented in Fig. 16. It shows a reduction on all the indicators for DW3, due to the material reutilisation during the end-of-life phase. Almost all the indicators were affected in a similar way, around 20% less with regard to DW1. LUP and MND were the only exceptions, for which a negligible difference was observed. It was justified because our main differences came from the reduction on aluminium consumption, and so, the reduction on electricity consumption from grid necessary to turn bauxite into aluminium. The electricity consumption has relatively small influence on LUP and MND [43].

Impact categories for DW1 vs DW3 were analysed in Fig. 17, 20% impact reduction for human health and resources consumption, and 20% impact reduction for ecosystem quality was achieved in DW3, with regard to DW1 and taking DX1 as reference. It was due to the material reuse counterbalance the raw material consumption in the manufacturing phase.

These results elucidate that the impact reduction obtained from the enhancement carried out in the end-of-life phase was more significant than the reduction obtained from the optimisation performed in the manufacture phase. It means that reusing of components generates a positive effect on the end-of-life phase, allowing a reduction on the overall impact for the complete experimental system. Therefore, re-using was an efficient way of improving the environmental impact of the system.

5.2.3. Design optimisation and materials reuse working together (DW4)

Fig. 18 shows the reduction on the climate change impact parameter achieved by the two improvements previously proposed working together (DW4) vs DW1. Particularly CEP, RPEP, CHP, RDEP, OLD, ETP, AP, LUP, MND and FFD indicators were investigated. The lowest values are presented in DW4 due to minor material consumption during the manufacturing phase and owing to the material reuse at the end-of-life phase. The most affected indicator in DW4 were CEP, REP, CHP, RDEP, OLD, ETP, AP and FFD. LUP and MND were only slightly affected due to the same reason detail in DW2 and DW3, the reduction in aluminium consumption gener-

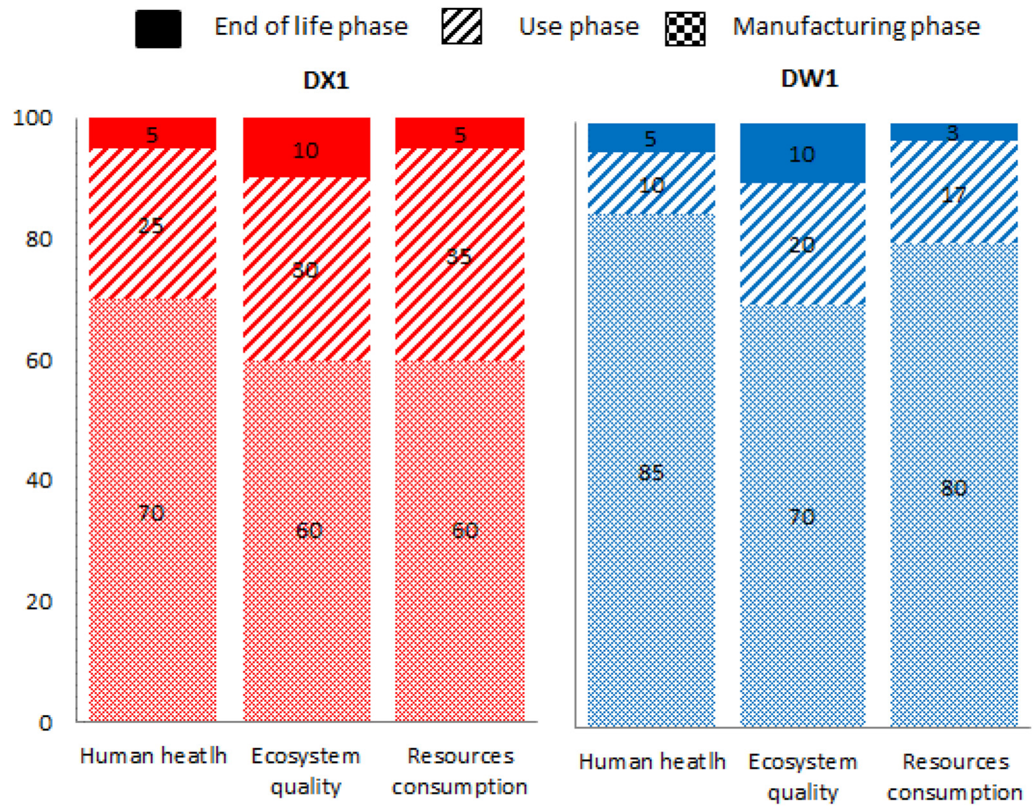

Fig. 12. Impact of the different life cycle phase for each impact category of the DW1 and DX1.

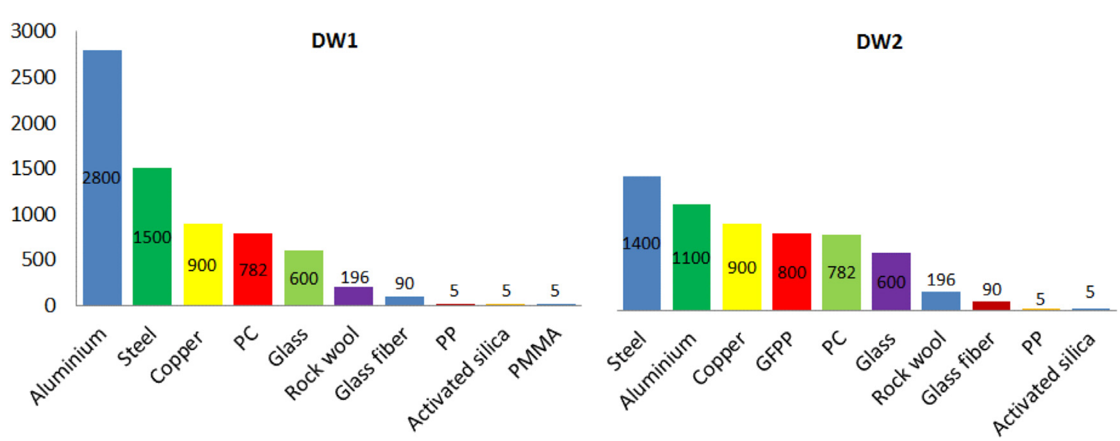

Fig. 13. SCP generated by each material during the manufacturing phase in DW1 and DW2.

ates a decrease in the consumption of electricity from the grid in the manufacturing phase, however, it has little influence on LUP and MND. On the one hand, CEP, RPEP, CHP and OLD were more affected by the improvement proposed in DW2, on the other hand AP and FFD more influenced by the improvement proposed in DW3. Regarding LUP and MND, the difference was negligible for the same explanation explained for DW2.

Fig. 19 compares the three impact categories for DW1 vs DW3. It was remarkable that when all the feasible optimisations were performed together (DW4) it was possible to reduce the impact up to 50% for human health, 22% for ecosystem quality and 40% for resources consumption (in DW4 versus DW1, taking as reference DX1). It means that the two proposed enhancements present a meaningful synergic effect, which led to a major reduction of the environmental impact in all those categories evaluated. The best results were observed in the human health impact category due to the proposed optimisations resulted mainly in a reduction of the CHP, OLD, CEP and RPEP indicators (Fig. 18) which affect directly to this specific impact category.

5.3. Influence of electricity consumption from grid

A sensitivity analysis was carried out in order to elucidate the effect of electricity consumption from grid on the environmental impact of the DW-based system. Fig. 20 compared the three impact categories for DW1, versus the same case with a 10% higher electrical consumption from grid, in the operational phase (DW5). Results showed that a slight deviation in energy consumption does not mean a significant variation in the value of those impact categories analysed.

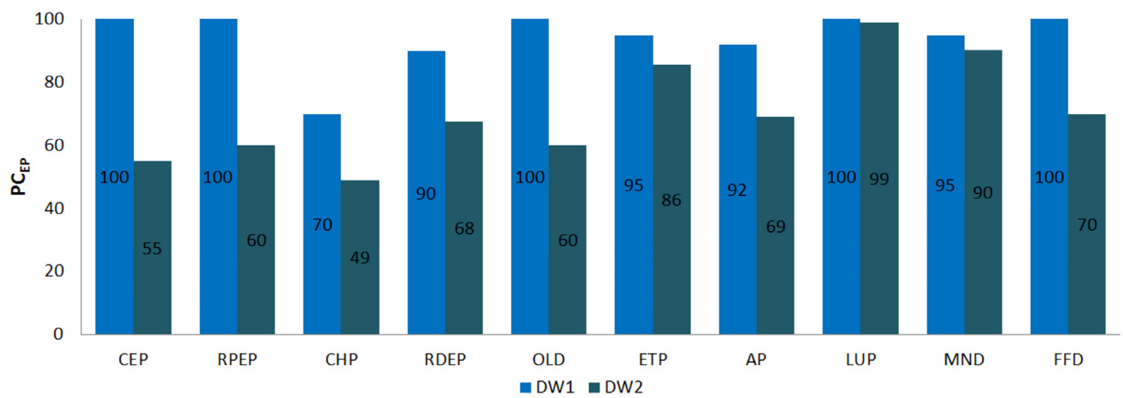

Fig. 14. Evaluation of impact indicator for DW1 vs DW2.

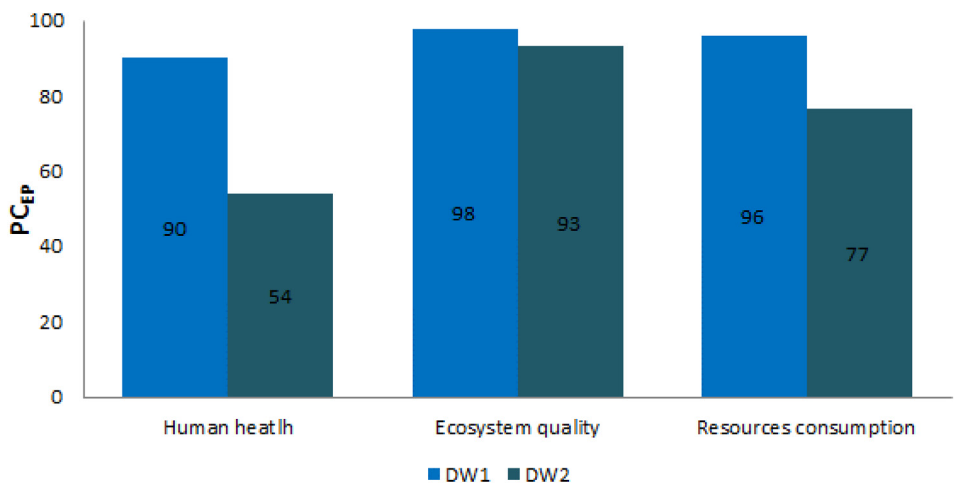

Fig. 15. Impact categories comparison for DW1 vs DW2.

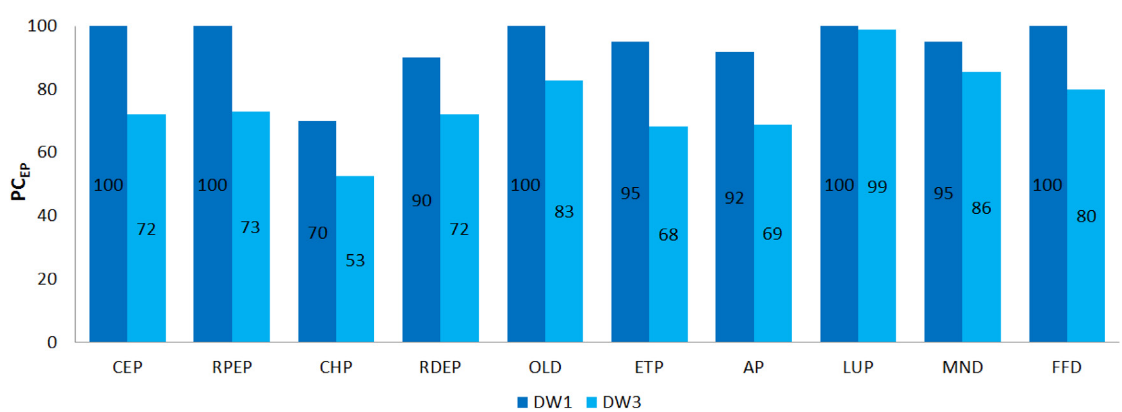

Fig. 16. Evaluation of environmental impact indicator for DW1 vs DW3.

The difference between DW1 and DW5 in terms of environmental impact was less than 5% for each impact category. It means that a deviation of 10% in electricity consumption during the operational phase does not significantly influence in the resulting impacts on human health, ecosystem quality and resources consumption.

5.4. Result comparison

In this section, the results obtained in this work are compared with those obtained by other authors in related works, the main characteristics of which were summarised in Table 1. Regarding the contribution of the different phases to the global impact, the manufacturing stage represents more than 50% of the total impact in all the impact indicators in almost all the studies previously considered. Specifically, in those works carried out by Beccali et al. [22] and Finochiaro et al. [18], the manufacturing stages accounted for more than 75% of the total impact, which is in agreement with the results of this work. However, the results obtained by Beccali et al. [10] are an exception, since in this study the operational phase presented the greatest contribution to the total environmental impact. This can be justified by the use of an auxiliary gas boiler

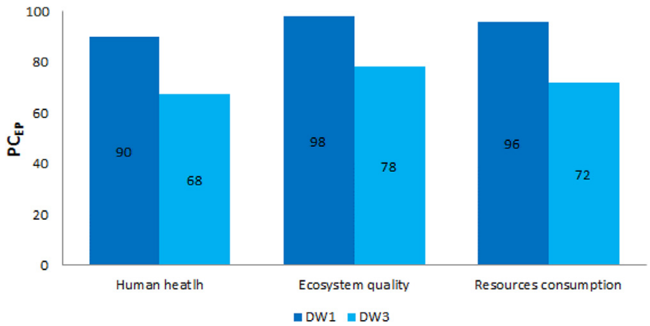

Fig. 17. Impact categories comparison for DW1 vs DW3.

and a conventional auxiliary chiller that consume electrical energy from the electrical grid during the operational phase. In addition, all the reported studies presented better results for the solar HVAC systems compared to conventional systems. General impact indicators such as global warming potential (GWP), carbon footprint, etc. were reduced by 24–40% in those investigations that achieved less improvement [11] and up to 70% in those that achieved better results [14].

6. Discussion

This discussion is focused on those LCA results for the 3 impact categories studied in the different systems considered in this work (Table 7). The PC_{EP} was calculated as a percentage change of DX1 system in all cases, which means that DX1 was always used as a reference. The results were classified into three parts, one for each of the three phases of the system life cycle: manufacturing, use, and end-of-life. The manufacturing phase took into account all the impacts associated to the transformation and assembly processes necessary from the raw material. The use phase mainly considered the energy consumption from the grid, and the end-of-life those impacts related to reuse and disposal operations.

The DX-based system presented a lower environmental impact than the DW-based system in all impact categories. Differences of 10%, 2%, and 4% were observed for human health, ecosystem quality, and resource consumption, respectively.

In terms of manufacturing, it represents between 70% and 85% of the total impact for the DW-based system and between 60% and 70% for the DX-based system. Total impact generated by the DX-based system during the operational phase was between 20% and 40%, while the total impact generated by the DW-based system ranged from 5% to 10%.

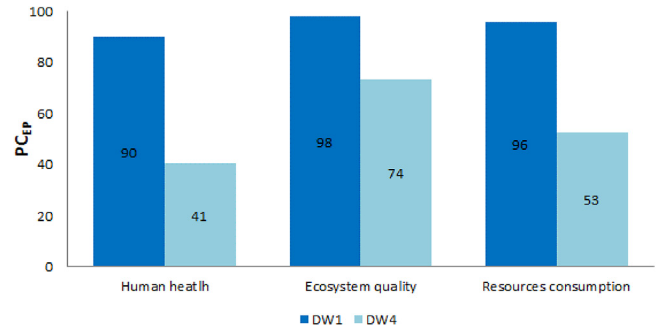

Fig. 19. Impact categories comparison for DW1 vs DW4.

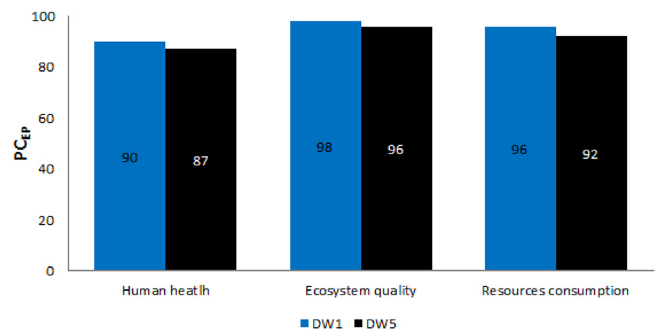

Fig. 20. Environmental impact categories comparison for DW1 vs DW5.

A proper DW-based system weight optimisation strategy could lead to a 30%, 5%, and 20% reduction in environmental impact for the categories of human health, ecosystem quality, and resource consumption, respectively. Additionally, reusing those materials used to manufacture DW-based systems could lead to a 20% reduction in the three impact categories studied. Eventually, combining both strategies, weight optimisation and material reuse, it was observed a synergy effect that led to a significant reduction of the impact associated to the different categories: up to 50% in human health, 22% in ecosystem quality and 40% in resource consumption.

Regarding the impact indicator, DW-based system presented a 30% lower CHP value than the DX-based system. The weight optimisation and material reuse strategies allow to achieve separately a reduction of 50% in CHP. Nevertheless, when the two strategies worked together, a reduction of up to 60% was achieved.

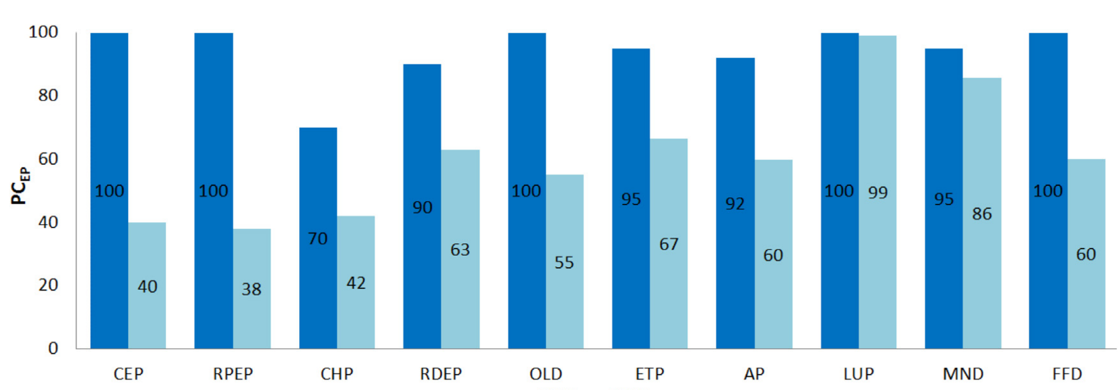

Fig. 18. Evaluation of impact indicator for DW1 vs DW4.

Table 7
PC_{EP} results of the different systems analysed, broken down into each of the 3 impact categories studied and contribution of each phase of the product life cycle.

	Human health	Ecosystem quality	Resources consumption	Human health	Ecosystem quality	Resources consumption
	DX1			DW1		
All life phases	100	100	100	90	98	96
Manufacturing phase	70	60	60	76,5	68,6	76,8
Use phase	25	30	35	9	19,6	16,32
End-of-life phase	5	10	5	4,5	9,8	2,88
	DW2			DW3		
All life phases	54	85	77	68	79	72
Manufacturing phase	35,1	63,75	53,9	54,4	59,25	57,6
Use phase	16,2	17	20,79	13,6	19,75	14,4
End-of-life phase	2,7	4,25	2,31	−13,6	−11,85	−18
	DW4			DW5		
All life phases	41	74	53	85,5	93,1	91,2
Manufacturing phase	28,7	48,1	39,75	64,13	60,52	68,4
Use phase	12,3	22,2	13,25	17,1	27,93	18,24
End-of-life phase	−8,2	−7,4	−11,93	4,28	4,66	4,56

7. Conclusion

In this work, a LCA of an experimental HVAC system based mainly on a desiccant wheel, DW, an indirect evaporative cooler, IEC, and a thermal solar system, compared to a conventional HVAC system based on a direct expansion unit, DX, were carried out using Ecoinvent 2017 database and Eco-indicator 99 methodology. Moreover, the influence of implementing some modifications based on the circular economy and eco-design guidelines, mainly focused on reducing the weight of the system and reusing materials at the end of its useful life, on the environmental performance of the experimental DW-based system was analysed.

DW-based system presented higher performance in terms of environmental impact indicators and impact categories than the DX-based system mainly owing to its less electrical energy consumption during the operational phase, counterbalancing the higher raw material consumption in the manufacturing stage. Differences between 2% and 10% were observed for the impact categories and between 0% and 30% on the impact indicators.

Regarding the life cycle phases of both DW and DX-based systems, LCA results elucidated that the manufacturing phase presented the greater influence on the environmental impact of the DW-based system, mainly due to the higher consumption of raw materials, especially steel and aluminium. However, the DX-based system consumed more electricity than the DW-based system during the operational phase. The impact generated by both systems during the end-of-life phase was very similar.

Weight optimisation and material reuse in DW-based system generated a significant impact reduction, between 22% and 50% for those impact categories analysed. It was mainly since the manufacturing phase was the stage with the higher effect on the total impact of this system and that the material reuse generated a positive effect, reducing the total environmental impact.

Concerning the environmental impact indicators, it is important to highlight the results obtained in terms of CHP due to the growing concern about climate change nowadays. By combining the two improvement strategies, it was possible to obtain a 60% reduction in CHP. In terms of LUP and MND, few differences were observed when the proposed strategies were analysed. It was due to the environmental benefit of reducing the consumption of steel and aluminium, which resulted in a lower consumption of electrical energy during the manufacturing phase without significantly affecting the LUP and MND indicators.

According to the sensitivity analysis performed, a 10% increase in electrical energy consumption during the DW-based system operational phase did not significantly modify the LCA results. It was owing to the main contribution to the environmental impact that was generated by the consumption of raw material during the manufacturing phase.

Based on the above, it can be concluded that the DW-based system presented slightly better environmental benefits than the DX-based system. Nevertheless, by reducing weight reduction and reusing components, it would be possible to significantly increase the environmental performance of the DW-based system. These results can be extrapolated to other similar solar HVAC systems, since in all of them, manufacturing is the phase with the greatest environmental impact according to the literature review. The results presented in this work support the development of new and more sustainable HVAC systems.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2021.111697.

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