LCA and techno-eco comparison between reference and new systems

IEA SHC TASK 53 | NEW GENERATION SOLAR COOLING & HEATING SYSTEMS (PV OR THERMALLY DRIVEN)

LCA and techno-eco comparison between reference and new systems

Marco Beccali1, Maurizio Cellura1, Sonia Longo1
June 2018
Task 53 / Report A5, http://dx.doi.org/10.18777/ieashc-task53-2019-0004

Institution *Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici – Università degli Studi di Palermo*
Address *Viale delle Scienze Ed.9, 90128 - Palermo*
Phone *+39-09123861911*
E-mail *marco.beccali@dream.unipa.it*

Contributors: Maria Anna Cusenza, Teresa Maria Gulotta, Daniel Mugnier, Valeria Palomba, Pedro G. Vicente Quiles, Tim Selke, Salvatore Vasta

Contents

1. Executive Summary

This technical report describes the research activities developed within Subtasks A: “Components, Systems & Quality, Activity A5 “LCA and techno-eco comparison between reference and new systems”.
Subtask A – Activity A5 is focused on environmental analysis and, when applicable, on the techno-economic analysis, of the systems studied in Subtask A, and the comparison with reference systems when accurate (same location and same boundary conditions).
In addition, Activity A5 is aimed at selecting adequate key performance indicators and at defining a quality-labeling scheme to be used for a clear and synthetic description of the main characteristics/impacts (technical, economic, energy, environmental, social) of solar heating and cooling systems.
Activity A5 also includes the development of a simplified tool for assessing the life cycle energy and environmental impacts/benefits due to the use of solar heating and cooling systems in substitution of conventional ones, considering specific climatic conditions.
Three deliverables are obtained:

- Activity A5-1: Report on environmental and techno-economic analysis of solar heating and cooling systems;
- Activity A5-2: Report on Key Performance Indicators (KPI) and quality-labeling scheme for solar heating and cooling systems;
- Tool ELISA for life cycle energy and environmental analyses of solar heating and cooling systems and user’s manual.

2. Activity A5-1

The main goal of this activity is to develop an environmental and, where possible, a techno-economic analysis of solar cooling systems. The first part of this section reports a summary of literature studies on the environmental analysis of solar heating and cooling systems, while the second part of the section includes environmental and, where possible, techno-economic analyses of the systems studied in Subtask A and the comparison with reference systems when accurate.

2.1 Literature studies on the life cycle assessment applied to solar heating and cooling systems for environmental analysis

In the scientific literature, different studies assessed the environmental performance of solar systems, also considering their life cycle. Some of them are summarized in the following.

Beccali et al. (2012) applied the Life Cycle Assessment (LCA) methodology to investigate the energy and environmental life cycle impacts of a solar heating and cooling (SHC) plant equipped with a water – ammonia absorption chiller (useful life of 25 years). In detail, two different back-up configurations of the SHC plant were examined: hot back-up and cold back-up. The LCA analysis was carried out considering two different localities (Palermo and Zurich) and a peak cooling demand of 12 kW. The system boundaries included the production phase (supplying raw materials and production/assembly of the main component of the plant), the use phase (including the life cycle of electricity and natural gas), the end-of-life phase (final treatments of waste due to the component of the plant). The main results of the study showed that for FU1, SHC plant in hot back-up configuration is the best configuration for both locations. The research highlighted the largest energy and environmental impacts (70-90%) due to the use phase and the negligible impacts of the end-of-life. The index Global Energy Requirement (GER) and Global Warming Potential (GWP) of SHC plants varied from 458 GJ and 27.6 tonCO_{2eq} (Palermo, hot back-up configuration) to 1,478 GJ and 79.2 tonCO_{2eq} (Zurich, cold back-up configuration). The life cycle performance of the system was compared to that of a conventional plant with a vapor compression chiller and a gas boiler. The innovative plant had a lower environmental impact than the conventional plant. Energy and CO_{2eq} emission payback times and the energy return ratio of the system, compared with the conventional one, were calculated. For all the analysed configurations they ranged from 4 to 6 years.

Beccali et al. (2014) applied the LCA methodology to compare a SHC system equipped with an absorption chiller and a conventional system, also assisted by a photovoltaic (PV) plant (grid connected and stand-alone). The analysis was performed considering three buildings, tailored to have the same peak cooling demand (12 kW), in three different locations: Palermo (southern Italy), Zurich (Switzerland) and Rio de Janeiro (Brazil). For all energy plants system boundaries include: supply raw materials, producing/assembly and maintenance/substitution of the main components of the plant; use phase (life cycle of electricity and natural gas consumed during the useful life time of the plant); the treatment of waste from the plant components at the end of life.

The results indicated that, in many cases, the conventional system with the PV grid connected plant performed best. The standalone PV assisted systems performed worse than the PV grid connected and the solar system in nearly all the analyzed cases, due to the high impact of the electricity storage life cycle. For all the examined locations the use phase is responsible of about 70–90% of the energy and environmental impacts of the plant life cycle.

Bukoski et al. (2014) applied the LCA to analyze the environmental impacts of implementing a solar/electric hybrid cooling system in a stadium of 15,000 seating capacity in Bangkok, Thailand. The life cycle emissions of the solar assisted absorption chiller system were compared to that of a conventional electricity-consuming vapor compression chilling system. The functional unit is the generation of 9,575 refrigeration tons (RFT)-hr per week of chilled water to be used in the heating, ventilation, and cooling (HVAC) system, for 30 years. The system boundaries include raw material extraction, processing, and manufacturing of all system components, the use phase, the-end-of life processes (recycling/landfilling) and the transportation during each phase of the life cycle. The results showed that the net life cycle impacts of the solar system are reduced of about 26–40%

when compared with those of the conventional one: the avoided impacts during the operation of the solar system outweigh the impacts caused during the remaining life cycle steps. The contribution of the use phase of the solar assisted system ranges from 19% (Acidification) to 56% (GWP), whereas conventional system use phase account for more than 74% for all examined impact categories. Thus, solar assisted AC system has much higher percentage contributions from non-use phases.

Florides et al. (2002) developed an energy, economic and environmental study of a domestic-size absorption solar cooling system with a useful life of 20 year. Different simulations of the use phase were developed, in order to optimize various factors affecting its performance: collector slope angle, storage tank size and collector area. The total equivalent warming impact (TEWI) of the system was compared to that of a conventional vapor compression air conditioner, satisfying the same load. From the optimization study resulted a system consisting in a 11 kW absorption chiller, 15 m^2 compound parabolic collector (CPC) tilted at 30° from horizontal, a 600 l hot water storage tank made of copper and thermally insulated with polyurethane and a 18 kW conventional boiler powered with diesel oil. The simulation of the use phase indicated that the annual cooling load of 17,600 kWh was covered with a total supply of 15,220 kWh of boiler heat, supplemented by 8,500 kWh of solar heat. The annual heating load of 3,530 kWh was covered with a total supply of 2,880 kWh of boiler heat and 1,500 kWh of solar heat. The economic analysis showed that the only economically viable solution was to use the CPC with a collector area of 15 m^2. From the environmental point of view resulted that for a service life of 20 years the TEWI is 90,000 kg CO_2. The TEWI of conventional system results 1.24 times greater than that of the absorption solar cooling system.

Gebreslassie et al. (2009) proposed a method for the design of the absorption cooling system that simultaneously considers the integration of LCA and process optimization to improve the economic and environmental performance of the system. The goal of the study was to identify the optimal design and associated operating conditions that simultaneously minimize the total annualized cost and environmental impact. The economic and environmental optimization was carried out developing a computer code for simulating the system. LCA study was made considering a cradle to grave approach. The environmental impacts were assessed through Eco-indicator 99 method. The solution of mathematical model was defined by a set of Pareto points that represent the optimal trade-off between economic and environmental aspects. From the study resulted that in the optimal environmental solution the Eco-indicator 99 is equal to 15.381 and the total annualized cost is 25.9% larger than in optimal total annualized cost solution for which Eco-indicator 99 is equal to 16.612.

Gebreslassie et al. (2010) developed an analysis based on a previous work (Gebreslassie et al., 2009) that integrated a solar thermal system into a thermal energy driven absorption cooling model and that performed a LCA of this integrated system in order to obtain a suitable environmental indicator to be optimized along with the standard economic criteria. The environmental assessment was done through LCA methodology and applying the Eco-indicator 99 method. The solution of the model was defined by a set of Pareto optimal points. The results of the study highlighted that a conflict exists between the cost and environmental impacts. It is possible to reduce up to 70.5% the environmental impact of the most profitable design, by increasing the cost in no more than 40%. This can be achieved by increasing the amount of solar collectors installed, which reduces the fossil fuel needs. In the minimum total cost Pareto design, the main source of impact was the operation of the gas fired heater, whereas the contribution of the construction phase of the cooling system was negligible. In the minimum environmental impact solution, the main contributor to the total impact was the operation of the solar collectors; in this case the contribution of the manufacturing phase was larger, mainly because of the emission of heavy metals. A significant reduction in environmental impact can be achieved increasing the numbers of collectors installed, which increases the solar fraction of the cooling system.

Hang et al. (2011) presented an energy, economic and environmental assessment of a solar cooling system for a medium-sized office building in Los Angeles. Further, the authors conducted a system performance optimization by varying two major parameters of the system. The system consists of evacuated tube solar collectors, a hot water storage tank, a single effect LiBr – H_2O absorption chiller, and a gas fired auxiliary heater. According to the peak load, the capacity of the chiller is equal to 150 kW. The energy performance of the system was assessed by varying storage tank volume (from 0.02 m^3/m^2 to 0.14 m^3/m^2) and collector area (from 80 m^2 to 490 m^2). The results showed that trade – off exist between economic and environmental/energy performance. Using the cost of CO_2 emission reduction as an indicator, the optimal solar cooling system configuration for the building has a solar collector area of 280 m^2, the storage tank volume to collector area ratio is 0.04 m^3/m^2, which corresponds to a tank of 11 m^3, the solar fraction is 83% and the cost of carbon footprint reduction of $0.75/kg. From the energy analysis resulted that the volume of the storage tank does not influence the system performance significantly when the collector area is small. If the volume is too large, a negative effect on the system performance is observed. The economic analysis showed that as the solar collector area increase, the solar cooling system becomes increasingly expensive, mainly due to the high initial cost of the solar collectors and absorption chiller. From the environmental analysis resulted that as the solar collector area increases, a CO_2 emission reduction is obtained.

Hang et al. (2014) developed a life cycle economic and environmental assessment of a solar cooling system with external compound parabolic concentrator solar collectors and an absorption chiller. A comparison of the solar system with a conventional one in two types of office buildings at three locations at California was performed. Two different solar cooling system configurations were considered: configuration 1 sizes the area of solar collectors and absorption chiller to meet the peak cooling demand, and uses natural gas as the only backup energy source; configuration 2 sizes the area of solar collectors and absorption chiller to meet half of the peak cooling demand, and uses natural gas as the backup energy source for the absorption chiller, while incorporates an electrical vapor compression chiller to meet the rest half of peak cooling demand. The results showed that configuration 2 achieved better life cycle economic and environmental performance than the configuration 1. In addition, solar system achieved lower present worth cost and reduced 35–70% carbon footprint during the entire life cycle than the conventional system.

Jing et al. (2012) evaluated the energy and environmental impacts a solar building cooling heating and power system driven by solar energy and natural gas, installed in a commercial office building in Beijing, China. The system boundaries include the supply of raw materials, the manufacturing of the system and the operation. The results, referred to GWP, acidification, respiratory effects and primary energy consumption indicated that the impacts are mainly caused by the operation and fuel production; the supply of raw materials also gives some contributions while other two stages have less significant influence on the final results.

Kalogirou (2009) developed a study of thermosiphon solar water heating systems showing that a considerable percentage of the hot water needs of a family of four persons can be covered with solar energy and a considerable amount of greenhouse gases can be avoided. The system has a payback time of 2.7 years and life cycle savings of 2,240 € with electricity backup (price of electricity: 0.153 €/kWh) and payback time of 4.5 years and life cycle savings of 1,056 € with diesel backup (price of diesel: 0.76 €/l). In addition, the energy spent for the manufacture and installation of the solar system is recovered in about 13 months, whereas the emission payback time varies from a few months to 3.2 years according to the fuel and the particular pollutant considered.

Marcos et al. (2011) examined an experimental solar energy facility made by flat plate vacuum solar collectors, designed to meet the heating demand in a typical Spanish dwelling. To produce solar-powered air conditioning in summer, an absorption chiller was fitted to the system. The solar facility was able to meet 65.3% of the space heating demand. For air conditioning, the system covered 46% of the demand, but with high indoor temperatures. The savings in CO_2 emissions afforded by the use of this facility compared to conventional air conditioning during the heating season ranged from about 557 kg of CO_2 (compared to a heat pump) to about 2,658 kg of CO_2 (compared to coal fuelled systems). The emissions reduction during the cooling season comes to approximately 555 kg of CO_2. An economic assessment of the system showed that the solar heating system would be amortized in 24, 28 or 22 years, depending on whether the energy replaced is electricity, natural gas or gas oil, respectively. The amortization period for the absorption chiller is 34 years, if the electrical consumption is not included. Otherwise, the solar cooling system could not be amortized.

Martinopoulos et al. (2013) investigated the influence from the use of different materials or/and techniques in the production of solar flat plate collectors used in domestic solar hot water systems. The examined systems cover the hot water needs of a typical three-person household in Greece, substituting electricity. The outcomes of the analysis highlighted that the examined system has a lower environmental impact than the substituted electricity. Furthermore, systems that employ better materials and/or manufacturing techniques and are characterized by a high thermal efficiency perform better, due to the increased thermal load that they can cover.

Martinopoulos and Tsilingiridis (2014) developed a technical and economic evaluation of a typical solar space and water heating system, used in a Greek detached house. Four climatic zones designated in the Greek

Regulation were examined. The analysis demonstrated that the use of a solar thermal system for space and water heating enables the minimization of energy costs as well as the subsequent air emissions. The solar coverage and discounted payback period are strongly influenced by the climatic zone of the building and the type of fossil fuel substituted. In all cases, the solar system covers at least 45% of the total heating loads while the payback period is less than 10 years considering natural gas substitution and as low as 4.5 years compared to oil. The abated CO_2 varied from 50 t in the case of natural gas to at least 65 t in the case of oil.

2.2 Life Cycle Assessment of a compact Desiccant Evaporative Cooling system

The results of this analysis were published in: P. Finocchiaro, M. Beccali, M. Cellura, F. Guarino, S. Longo, Life cycle assessment of a compact desiccant evaporative cooling system: the case study of the "Freescoo", Solar Energy Materials and Solar Cells, 156, (2016), 83-91.

2.2.1 The examined system

The examined product (Figure 2.2.1.1) is a system designed for air-conditioning in buildings. The system is composed by a solar photovoltaics/thermal air collector, two adsorption beds, an integrated cooling tower, two wet heat exchangers, fans, batteries and all other auxiliaries needed to perform the air handling process also in stand-alone operation. During winter, if solar radiation is available, warm air can be delivered to the building.

Figure 2.2.1.1: Freescoo unit

The system integrates solar photovoltaic and thermal collectors, which provide, respectively, electricity used for the machines and heat for the regeneration of the desiccant material. Peak power of the PV is about 170 W. A battery system is used to store electricity produced from PV (65 Ah). If solar PV electricity is not sufficient to drive the system, it commutates automatically to the grid. The system uses two fixed desiccant packed-beds of silica gel, which are operated in a batch process, and two wet evaporative heat exchangers connected in series. Each adsorption bed is made by a fin and tube heat exchanger with the gaps between the fins filled with silica gel grains. The adsorption material is cooled by water flowing through the tubes. A system of air dumpers provides the commutation between the two adsorption beds in order to guarantee a continuous dehumidification process of fresh air. A cooling tower, which is integrated in the system, is used to reject the adsorption heat generated by the desiccant bed operating in dehumidification mode. Regeneration of the adsorbent is carried out using the heat delivered by the solar air collector.

The thermodynamic cycle of the process air is described in Figure 2.2.1.2 and Table 2.2.1.1. A flow rate of outside air (1) is drawn through one of the adsorption beds for its dehumidification and partial cooling. Due to the simultaneous moisture and heat exchange, dehumidification process is carried out at almost constant temperature (1–2). Afterwards, dehumidified air (2) is mixed with the return air from the building (4), reaching the conditions of point (3). The mixed air, which has a flow rate equal to 140% of the air flow rate supplied to the building, enters the wet heat exchangers reaching the supply conditions at point (5). In order to produce the cooling effect, at the outlet of the second wet heat exchanger, a portion of the air flow rate equal to 40% is drawn to the secondary side (5–6). The heat released in the adsorption bed is rejected through a water loop which is connected to the cooling tower (6–7) integrated into the system. The air flowing through the cooling tower comes from the secondary side of the wet heat exchangers, which allow low supply temperatures to the room and higher overall energy performances.

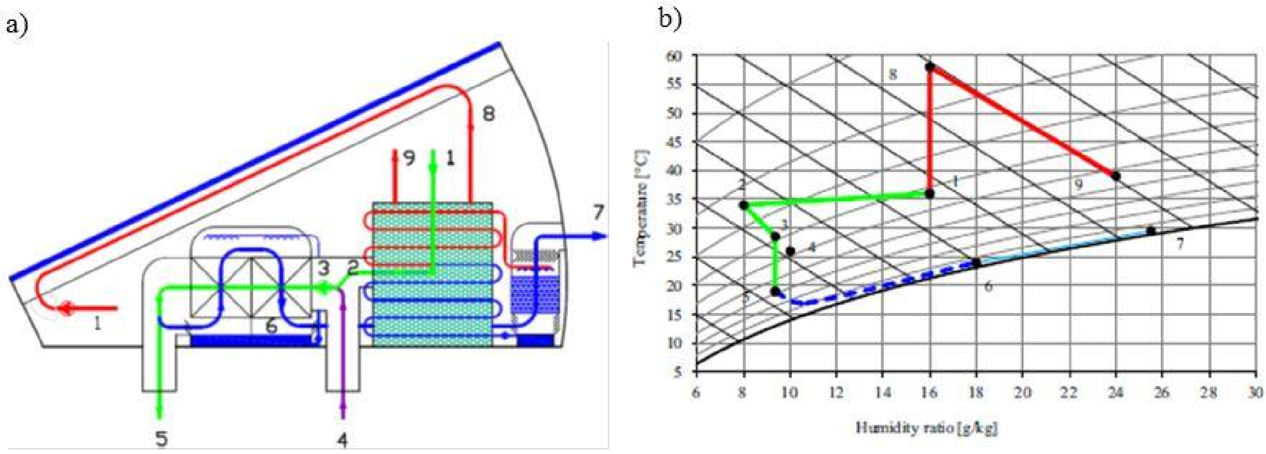


Figure 2.2.1.2: a) Schematics of the system; b) Moist transformations

The rated air flow rate is 500 m^3/h whereas the maximum total cooling power is 2.7 kW at summer conditions ($T_{outside}$ = 36 °C, $RH_{outside}$ =50%, T_{bui} = 26 °C, RH_{bui} = 50%). Cooling power can be controlled through a variable volume strategy by changing the speed of the fans. System integrates a solar PV/thermal air collector having a collector surface of 2.4 m^2 which provides the heat for the regeneration of the desiccant material. All electric components are DC driven, this permitting a direct connection with the PV/batteries controller, without the use of DC/AC converters. Electricity is only used to drive the fans, the circulation pumps and other auxiliaries with a maximum power of 150 W.

Table 2.2.1.1: Thermodynamic cycle on a psychrometric chart

		Description	x [g/kg]	T °C	h [kJ/kg]
Process air	1	Outside air	16	36	77.2
	2	Adsorption bed	8	34	54.6
	3	Mixing	9.4	28.6	52.6
	5	Outlet Wet HX - prim	9.4	19	42.8
Building	4	Return air	10	26	51.6
Secondary air in Wet HX	5	Inlet Wet HX - sec	9.4	19	42.8
	6	Outlet Wet HX - sec	10.7	17	44.2
Cooling tower	6	Inlet CT	18	24	69.9
	7	Outlet CT	25.5	29.5	94.8
Regeneration air	1	Outside air	16	36	77.2
	8	Solar collector	16	58	100
	9	Outlet desorption	24	39	100.9

2.2.2 Life Cycle Assessment

Goal of the study

The goal of the study is to assess the energy and the environmental life cycle impacts of a compact Desiccant Evaporative Cooling system called “Freescoo” and compare its performance with a conventional air conditioning system. The analysis is carried out by applying the Life Cycle Assessment (LCA) methodology in compliance with the international standards of series ISO 14040 (ISO, 2006a, 2006b).

Functional unit and system boundaries

The selected functional unit (FU) is represented by a system providing heating (283 kWh/year) and cooling (1199 kWh/year) needs in a non-residential building during office hours in a lifespan of 15 years. The system boundaries include the following life cycle phases:

- Manufacturing (raw material supply, materials production, manufacturing/assembly of the main components of the system);
- Operation;
- End-of-life.

The installation and maintenance steps and the transport of the systems components from their production site to the installation one are not considered due to the lack of reliable information.

Impact assessment methodology and impact categories

The following energy and environmental indexes are selected to illustrate the energy and the environmental performance of the examined system:

- Global energy requirement (GER);
- Global warming potential (GWP);
- Ozone depletion (ODP);

- Human toxicity, non-cancer effects (HT-ce);
- Human toxicity, cancer effects (HT-nce);
- Particulate matter (PM);
- Ionizing radiation, HH (IR-hh);
- Ionizing radiation, E;
- Photochemical ozone formation (POFP);
- Acidification (AP);
- Terrestrial eutrophication (T-EU);
- Freshwater eutrophication (F-EU);
- Marine eutrophication (M-EU);
- Freshwater ecotoxicity (F-E);
- Land use (LU);
- Water resource depletion (WRD);
- Mineral, fossil & renewable resource depletion (MFRRD).

The characterisation models used for the impact calculations are the Cumulative Energy Demand (CED) (Frischknecht et al., 2007) method for the energy impacts, and ILCD 2011 Midpoint method for the environmental impacts (European Commission - Joint Research Centre, 2012).

Data quality

The eco-profiles of materials and energy sources used to produce the main components of the analysed FU are based on the Ecoinvent database (Frischknecht et al., 2005; Wernet et al., 2016).

Impacts of end-of-life are calculated by using the following databases:

- Buwal 250 in the case of recycling (BUWAL250, 1998);
- Ecoinvent for landfilling (Frischknecht et al., 2005);
- ETH-ESU for the end of life of the solar panels (E.U.ESU Group, 1996);
- European Reference Life Cycle Database (ELCD) for the iron metals (Joint Research Center, 2016).

Life Cycle inventory analysis

Data collection: Manufacturing phase

The data needed to assess the energy and environmental impacts of the FU are obtained from the direct measurement of the size and mass of each component and technical datasheets of each component of the system.

The data collection process involved the following equipment:

- Two adsorbent beds filled with silica-gel;
- Two Pb–Ca solar batteries, 12V 65Ah;
- Air ducts connecting the evaporative cooling module and the evaporative tower;
- Electric components, including electric wires and junction boxes;
- Two 38 W circulation pumps;
- Solar photovoltaic panel (power 170W, height per length 1150mm*966mm) and solar thermal panel (aluminium based, $TiNO_X$ coating (0.3 µm), and quartz glass(0.3 µm));
- Two electro valves;
- Three polyester-based air filters;
- Ethylene propylene diene monomer (EPDM) thermal insulation;

- Evaporative cooling module, including hydraulics components and two heat evaporative heat exchangers;
- Galvanized steel bars utilized for the case;
- Fuse box;
- Control board with micro-controller governing all the electricity driven equipment;
- Servo-motor for rolling shading devices;
- Internal frame;
- Steel frame;
- Evaporative tower;
- Hydraulic components;
- Four ways air valve displaced among the two adsorbent beds;
- Two fans with 190 and 300 mm diameter.

Data collection: Operation phase

In order to assess the primary energy consumption and related environmental impacts due to the operation phase, monitoring studies of a "Freescoo" unit installation have been performed. Results here presented are based on heating and cooling operation of a unit installed at the Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici (DEIM) of the University of Palermo, Italy. Data have been registered during July and August 2015 for summer operation and between January and February 2015 for winter operation.

Through the monitoring process the data described in Tables 2.2.2.1 and 2.2.2.2 have been estimated and implemented in the LCA model. Table 2.2.2.1 refers to the cooling season, while Table 2.2.2.2 to the heating one, in the form of average daily data. A heating period of 121 days and a cooling period of 90 days were considered to assess yearly impacts. Average monitored data are used to extrapolate seasonal performance for the whole heating (12 h a day) and cooling (8 h a day) season length. For the whole year, 113.4 kWh of total electricity consumption is considered for the yearly use phase calculation, of which only 24.9 kWh are imported from the grid. 2590 l of water have been considered as well. A useful life of 15 years is expected for the system.

Table 2.2.2.1: Cooling season, use phase data

Cooling energy delivered to the building	kWh/day	13.32
Electricity consumed (cooking mode)	kWh/day	1.04
Electricity from the grid (cooking mode)	kWh/day	0.26
Water consumption	l/day	28.78

Table 2.2.2.2: Heating season, use phase data

Solar heat produced (including ventilation)	kWh/day	6.1
Electricity consumed (heating mode)	kWh/day	0.17
Electricity from the grid (heating mode)	kWh/day	0.01
Sensible heating energy delivered to the building	kWh/day	2.34
Water consumption	l/day	0

Data collection: end-of-life phase

In the end-of-life phase it has been considered the recycling for glass based materials, landfill disposal for the solar PV/thermal modules and silica based components, rock wool and paints. No credit for recycling is associated to the end-of-life phase.

Life cycle impact assessment and interpretation

All the life cycle impacts are shown in Table 2.2.2.3.

Table 2.2.2.3: Life cycle impacts of the Freescoo system

Impact categories	Manufacturing	Operation	End-of-life	Total
GER (MJ)	2.72E+04	4.03E+03	4.64E+03	3.59E+04
GWP (kg CO_{2eq})	1.59E+03	2.40E+02	3.16E+02	2.15E+03
ODP (kg CFC-11_{eq})	1.61E-04	2.10E-05	3.69E-05	2.19E-04
HT-ce (CTUh)	6.91E-04	1.04E-05	8.64E-06	7.10E-04
HT-nce (CTUh)	2.28E-03	4.28E-05	4.16E-05	2.36E-03
PM (kg $PM2.5_{eq}$)	1.19E+00	9.05E-02	5.31E+02	5.32E+02
IR-hh (kBq $U^{235}{}_{eq}$)	3.68E+02	4.40E+01	1.81E-01	4.12E+02
IR-e (CTUe)	1.11E-03	1.41E-04	4.17E-07	1.25E-03
POFP (kg $NMVOC_{eq}$)	5.20E+00	6.30E-01	1.01E+00	6.84E+00
AP (molc $H^{+}{}_{eq}$)	1.15E+01	1.41E+00	1.56E+00	1.45E+01
T-EU (molc N_{eq})	1.69E+01	2.14E+00	3.14E+00	2.22E+01
F-EU (kg P_{eq})	1.56E+00	6.95E-02	3.62E-03	1.63E+00
M-EU (kg N_{eq})	1.64E+00	2.02E-01	2.89E-01	2.13E+00
F-E (CTUe)	5.52E+04	1.05E+03	1.84E+02	5.64E+04
LU (kg $C_{deficit}$)	1.79E+03	2.63E+02	1.47E+00	2.05E+03
WRD ($m^3 water_{eq}$)	4.60E+03	2.59E+02	6.60E-01	4.86E+03
MFRRD ($kgSb_{eq}$)	3.12E-01	8.64E-04	2.43E-05	3.13E-01

The share of each life cycle impact on the total impacts is shown in Figure 2.2.2.1 The manufacturing phase has a predominant weight in most of the indicators, reaching values above or close to 95% in the case of the indicators WRD, F-E, F-EU, HT-nce, HT-ce. Moderately lower impacts are reported and always higher than 70% for all other impacts, the lowest being ODP at 73.55%. Since the manufacturing phase is largely the most relevant among all the others, some further insights will be discussed on this phase. The most impacting components are the adsorbent bed, the solar batteries, the PV/thermal system, the air filters, the evaporative cooling module, the external, internal and steel frames. The sum of the impacts for these components is higher than 85% of the total impacts for all the indicators, the only exception being ODP reaching 79.91%.

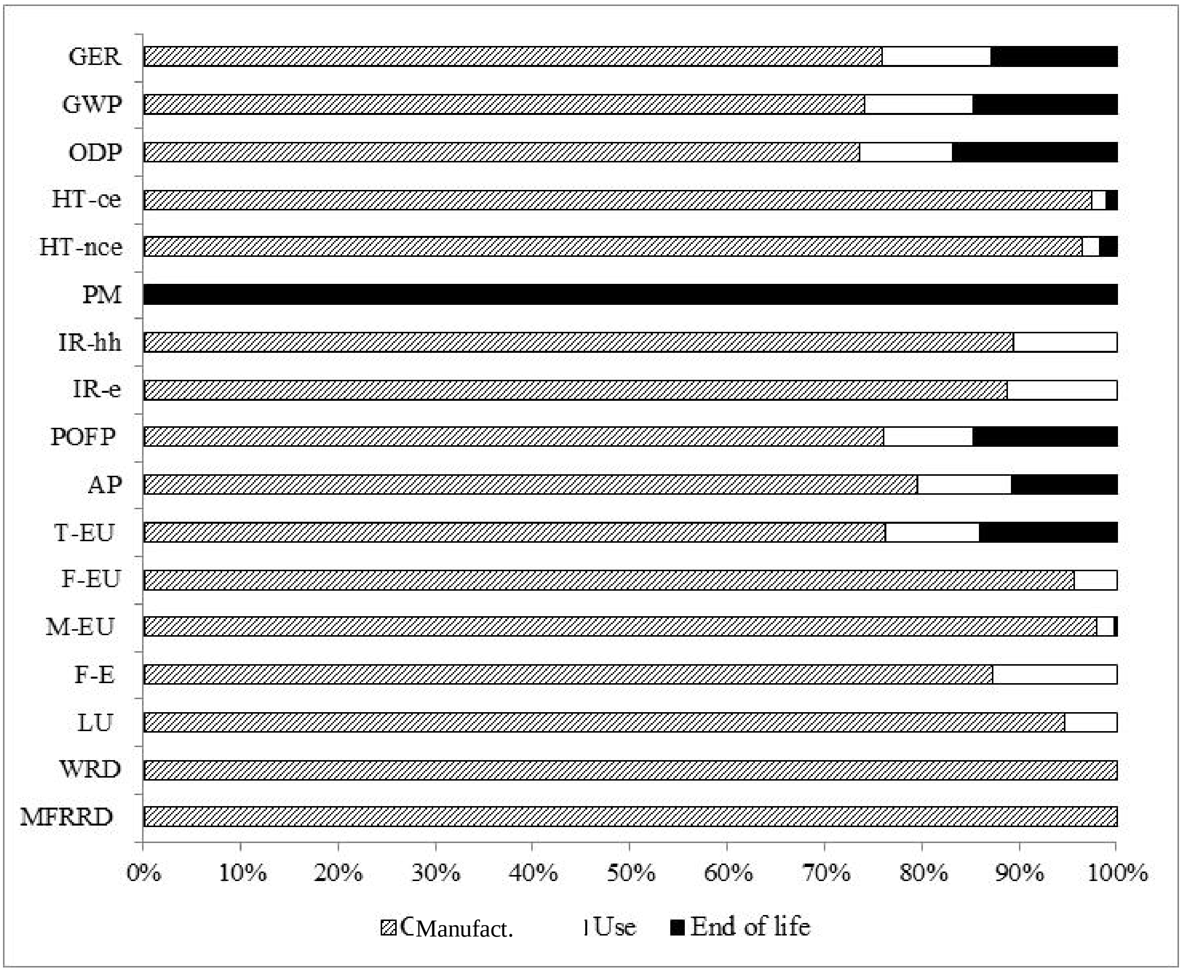


Figure 2.2.2.1: Impacts assessment: share of each life cycle step on the total impacts

Impacts related to each component are briefly discussed in the following bullet points:

- the highest share of impacts are associated to the adsorbent bed, ranging from the 5.53% of the ODP and the 22.85% of the LU;
- for solar batteries the most relevant indicators are HT-nce (48.39%), F-EU (43.72%) and F-E (46.06%). The other indicators range between the 10.80% of the HT-ce to the 27.85% of the AP;
- the photovoltaic–thermal system impacts share varies between 13.27% of the indicator HT-nce and 21.67% of M-EU. HT-nce (7.73%), F-E (7.14%) and ODP (37.40%) are outside the overall trend;
- the air filters have a less relevant role, since their impact would range in most cases between the 4.35% (ODP) and 6.70% (GER). HT-nce, F-UE and F-E would fall below the lower threshold;
- the evaporative cooling modules impacts the total between the 9.18% of the POFP to the 13.19 of IR-e. Only some indicators, such as HT-nce (3.81%), F-EU (5.92%) and F-E (5.51%) are below 6%;
- the external frames impacts are variable between the 3.18% of HT-nce to the 10.34% of HT-ce;
- the internal frames results variation range is included between 3.48% of ODP and 7.08% of the GER;
- the steel frames impacts vary between the 2% of WRD to the 5% of GWP. The only indicator outside the trend is the HT-ce, reaching the 10.87% of the overall impact.

For the comparison, the same impact categories assessed for Freescoo have been evaluated for the conventional system. The conventional system is a heat pump that generates the same heating and cooling described in Tables

2.2.2.1 and 2.2.2.2 for the Freescoo case with an average seasonal cooling mode Energy Efficiency Ratio (EER) of 3.0, a heating mode EER of 3.3, and a 2.7 kW cooling maximum power.

The conventional system impacts are shown in Table 2.2.2.4. In the end, the overall life cycle of the conventional system is compared with the one of the Freescoo and the differences between all impacts are reported in Table 2.2.2.5. The general trend shows values higher in nearly all impacts for manufacturing and end-of-life for the Freescoo: values ranging from 72% (GWP) to 92% (GER) are reported for the manufacturing step, while from 88% (AP) to 100% (IR and LU) are found in the end-of-life step. Operation phase is for all indicators much higher in the case of the conventional system. This leads to the following results for the overall life cycle:

- Most indicators report lower impacts for the Freescoo, e.g. GER and GWP are higher respectively by 186% and 201.56% in the case of the conventional system, land use marks the highest difference (221.58%),
- The only indicators reporting higher values for the Freescoo are: HT-ce and HT-nce (higher in the case of Freescoo by respectively 55.27% and 28.46% if compared to the conventional system), F-E (30.11%) and MFRRD (89.25%). These values are mostly due to larger impacts in the manufacturing phase, due to a large extent to solar batteries.

Table 2.2.2.4: Overall impacts of the conventional system

Impact categories	Manufacturing	Operation	End-of-life	Total
GER (MJ)	2.20E+03	1.00E+05	5.61E+02	1.03E+05
GWP (kg CO_{2eq})	4.47E+02	6.00E+03	3.63E+01	6.48E+03
ODP (kg CFC-11_{eq})	8.66E-03	5.26E-04	2.79E-06	9.19E-03
HT-ce (CTUh)	6.05E-05	2.56E-04	1.09E-06	3.18E-04
HT-nce (CTUh)	6.24E-04	1.06E-03	3.87E-06	1.69E-03
PM (kg $PM2.5_{eq}$)	1.16E-01	2.26E+00	6.66E-03	2.38E+00
IR-hh (kBq $U^{235}{}_{eq}$)	4.12E+01	1.09E+03	0.00E+00	1.13E+03
IR-e (CTUe)	1.25E-04	3.50E-03	0.00E+00	3.63E-03
POFP (kg $NMVOC_{eq}$)	4.32E-01	1.57E+01	1.09E-01	1.62E+01
AP (molc $H^{+}{}_{eq}$)	1.40E+00	3.51E+01	1.89E-01	3.67E+01
T-EU (molc N_{eq})	1.49E+00	5.34E+01	3.42E-01	5.52E+01
F-EU (kg P_{eq})	3.50E-01	1.72E+00	4.49E-04	2.07E+00
M-EU (kg N_{eq})	1.35E-01	5.05E+00	3.14E-02	5.22E+00
F-E (CTUe)	1.34E+04	2.60E+04	2.09E+01	3.94E+04
LU (kg $C_{deficit}$)	1.25E+02	6.50E+03	0.00E+00	6.63E+03
WRD ($m^3 water_{eq}$)	1.28E+02	6.45E+03	5.40E-02	6.58E+03
MFRRD ($kgSb_{eq}$)	3.21E-02	1.44E-03	4.51E-07	3.35E-02

Table 2.2.2.5: Overall impacts of the conventional system

Impact categories	Freescoo	Conventional system	Difference
GER (MJ)	3.59E+04	1.03E+05	-6.69E+04
GWP (kg CO_{2eq})	2.15E+03	6.48E+03	-4.34E+03
ODP (kg CFC-11_{eq})	2.19E-04	9.19E-03	-8.97E-03
HT-ce (CTUh)	7.10E-04	3.18E-04	3.92E-04
HT-nce (CTUh)	2.36E-03	1.69E-03	6.77E-04
PM (kg $PM2.5_{eq}$)	5.32E+02	2.38E+00	5.30E+02
IR-hh (kBq $U^{235}{}_{eq}$)	4.12E+02	1.13E+03	-7.19E+02
IR-e (CTUe)	1.25E-03	3.63E-03	-2.37E-03
POFP (kg $NMVOC_{eq}$)	6.84E+00	1.62E+01	-9.40E+00
AP (molc $H^{+}{}_{eq}$)	1.45E+01	3.67E+01	-2.22E+01
T-EU (molc N_{eq})	2.22E+01	5.52E+01	-3.31E+01
F-EU (kg P_{eq})	1.63E+00	2.07E+00	-4.37E-01
M-EU (kg N_{eq})	2.13E+00	5.22E+00	-3.09E+00
F-E (CTUe)	5.64E+04	3.94E+04	1.70E+04
LU (kg $C_{deficit}$)	2.05E+03	6.63E+03	-4.57E+03
WRD (m^3water_{eq})	4.86E+03	6.58E+03	-1.72E+03
MFRRD ($kgSb_{eq}$)	3.13E-01	3.35E-02	2.79E-01

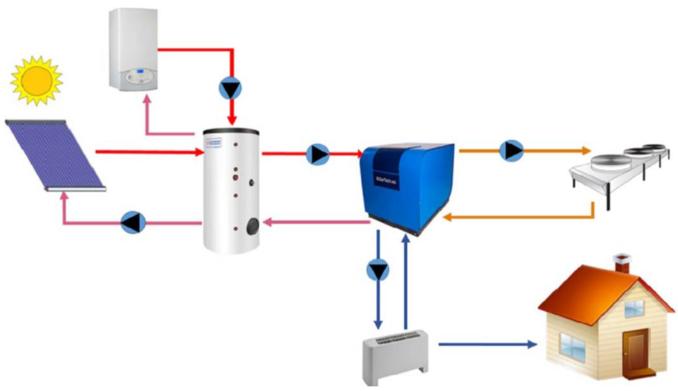
2.3 Life Cycle Assessment and techno-economic data of small size residential solar heating and cooling systems equipped with adsorption chillers

The results of this analysis were published in: S. Longo, V. Palomba, M. Beccali, M. Cellura, S. Vasta, Energy balance and life cycle assessment of small size residential solar heating and cooling systems equipped with adsorption chillers, Solar Energy 158 (2017), 543-558.

2.3.1 The examined system

The examined system is a system solar and heating cooling (SHC) system showed in Figure 2.3.1.1, where a field of solar thermal collectors connected to a thermal storage tank provides the driving energy to an adsorption chiller (10 kW). The process heat of the adsorption system is rejected to the environment by using a dry cooler, while the chilled water produced is sent to fan coil units for controlling the temperature of the building. A back-up unit is also part of the layout, consisting in a natural gas boiler.

Two different operating modes have been considered for summer and winter conditions: during summer, the adsorption chiller provides the cooling energy needed for air conditioning; during winter, the energy needed for space heating is provided by the solar thermal panels and, if needed, integrated by the gas heater.



- **Figure 2.3.1.1** Schematic layout of the SHC system.

The SHC system was compared with a reference system that uses a vapour compression water-water chiller/heat pump, with R410A as refrigerant and a nominal cooling capacity of 10 kW, both for the provision of space heating and cooling. Like the SHC system, it uses a dry cooler for the rejection of condensation heat into the environment. A schematic layout of the reference system is shown in Figure 2.3.1.2.

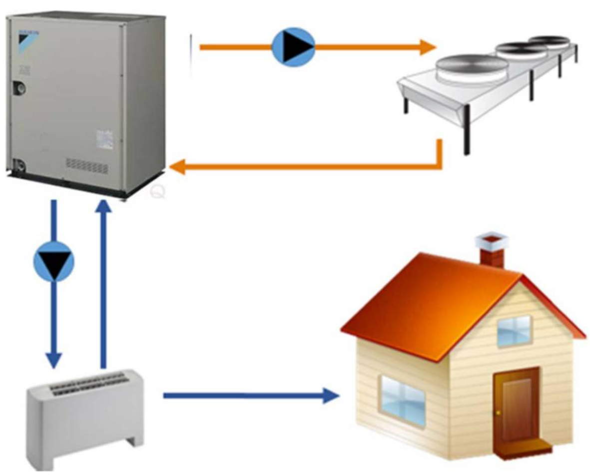


Figure 2.3.1.2 Schematic layout of the reference SHC system.

The two heating and cooling systems were sized to provide space conditioning for a building that is a class A+ single house having bearing structures in XLAM wood panels and thermal insulation in wood fibre and mineral wood, sited in Messina (Italy). Total surface and volume of the building are 130 m^2 and 728 m^3, respectively. The details on the parameters used for the simulation of the building, in terms of occupation profiles, internal gains and infiltration are given in Table 2.3.1.1. Data on the heating and cooling loads were used as input for the sizing of the solar thermal system.

Table 2.3.1.1 Main parameters for the simulation of the reference building

Parameter	Value
Infiltration rate	0.3 [vol h^{-1}]
Ventilation rate	2.64 [vol h^{-1}]
Heating set-point	20 [°C]
Cooling set-point	26 [°C]
Internal gains	10 W/m^2 due to lighting for 7 h/day
	600W due to electric appliances for 7 h/day
Occupation profile	4 people from 12:00 p.m. to 08:00 a.m. and from 6 p.m. to 12:00 p.m. during workdays
	2 people from 08:00 a.m. to 6:00 p.m. during workdays
	4 people for 24 h during weekends

2.3.2 Techno-economic data

The economic assessment of the system indicates that the current price of the SHC system defined by the supplier/vendor is 16,000 €, while current price of the conventional system used for the comparison is 4,860 €.

In addition, the cost for the maintenance of the SHC system is 80.00 €/year, while the maintenance of the conventional system is 96.00 €/year.

The system has an average COP_{th} of 0.45 and a Solar Electric Performance Coefficient ($COP_{Elec\text{-}sol}$) of 7.68

2.3.3 Life Cycle Assessment

Goal and scope definition

The goals of the study are to assess the energy and the environmental life cycle impacts of a SHC system equipped with an adsorption chiller and to compare it with those of a conventional system that performs the same function employing a vapour compression unit. In addition, the analysis aims at identifying the life cycle steps and the components of the SHC and the conventional system characterized by the higher impacts, and the influence of the useful life of both systems on the results.

The analysis is carried out by applying the Life Cycle Assessment (LCA) methodology in compliance with the international standards of series ISO 14040 (ISO, 2006a, 2006b).

Functional unit and system boundaries

The selected functional unit (FU) is represented by a system with a useful life of 10 years that provides cooling and heating for the building described in section 2.3.1, considering a cooling solar fraction of about 0.85.

The analysis followed a “from cradle to grave approach” including the raw materials supply, the manufacturing of the system, its operation and end-of-life. The transports, installation and maintenance steps were not taken into account due to data unavailability. However, their impact on global energy consumption and the environment can be considered likely negligible (Kalogirou, 2009).

Impact assessment methodology and impact categories

The following energy and environmental indexes are selected to illustrate the energy and the environmental performance of the examined system:

- Global energy requirement (GER);
- Global warming potential (GWP);

In addition, the energy payback time (EPT), GWP payback time (GWP-PT) and energy return ratio (ERR) were calculated by using the following equations:

$$EPT = \left(GER_{SHC-System} - GER_{Conv-System}\right) / E_{year} \quad (1)$$

where $GER_{SHC\text{-}System}$ and $GER_{Conv.\text{-}System}$ are, respectively, the primary energy consumed during life cycle of the SHC and the conventional system except for the operation phase; E_{year} is the net yearly primary energy saving due to the operation of the SHC system;

$$GWP - PT = \left(GWP_{SHC-System} - GWP_{Conv-System}\right) / GWP_{year} \quad (2)$$

where $GWP_{SHC\text{-}System}$ and $GWP_{Conv.\text{-}System}$ are, respectively, the GWP generated during the life cycle of the SHC and the conventional system except for the operation phase; GWP_{year} is the net yearly avoided GWP due to the operation of the SHC system;

$$ERR = E_{Overall} / GER_{SHC-System} \quad (3)$$

where $E_{Overall}$ is the net primary energy saving during the overall lifetime of system.

The characterisation models used for the impact calculations are the Cumulative Energy Demand (CED) method (Frischknecht et al., 2007) for the energy impacts and the IPCC2013 method (Stocker et al., 2013) for the GWP indicator.

Life Cycle inventory analysis

The inventory analysis has been carried out to quantify the inputs and outputs of the examined systems by means of a bill of materials and energy balance. In detail, the following input data were collected:

- A list of components that are part of the SHC and the conventional system and their technical characteristics. In detail, the SHC system has the following components: a 10 kW adsorption chiller, a 18 kW auxiliary gas boiler, solar thermal collectors (38.95 m^2), a heat storage (500 l), a 29 kW dry cooler, 50 m of pipes, 7 pumps. The conventional system is made by a 10 kW heat pump, 25 m of pipes, 2 pumps.
- The water consumption for the SHC system equal to 7560 kg;

- The yearly electricity consumption obtained from a TRNSYS simulation is 274 kWh/year for cooling season and 86 kWh/year for heating season. The yearly energy consumption from natural gas is 1462 kWh/year in cooling season and 533 kWh/year for heating season. For the reference system, the electricity consumption in the cooling season is 1417 kWh/year and in the heating season is 582 kWh/year;
- The useful life of the systems is 10 years and the days per year of operation are equal to 150 in cooling season and 110 in heating season.

Data have been elaborated with the a LCA tool developed in the framework of the International Energy Agency SHC Task 48 (Beccali et al., 2016).

Tables 2.3.3.1 and 2.3.3.2 show the data entry process in the LCA tool for the SHC and the conventional system.

Table 2.3.3.1: Input data for the SHC system

Components of the SHC system	**U.M.**	**Quantity**
Absorption chiller (8 kW)	unit	1.25
Auxiliary gas boiler (10 kW)	unit	1.8
Evacuated tube collector	m^2	38.952
Heat storage (2000 l)	unit	0.25
Heat rejection system (24 kW)	unit	1.21
Pipes	m	60
Pump (40 W)	unit	7.125
Water	kg	7560
Energy sources		
Electricity, low voltage, Italy (including import)	kWh/year	360
Natural gas, burned in boiler atmospheric burner non - modulating, < 100 kW, Europe	kWh/year	1995
Other information		
Useful life of the system	year	10

The specific impacts of components and energy sources have been gathered from the following studies/databases:

- The impacts of adsorption chiller (8 kW) and heat rejection system are referred to (Beccali et al., 2012);
- The impacts of electricity, natural gas, ammonia, auxiliary gas boiler, conventional chiller, evacuated tube collectors, glycol, heat storage, pipes, pump and water are referred to (Frischknecht et al., 2007b).

The specific impacts of electricity generation, distribution and use are representative of the specific geographic context where the systems are installed. The specific impacts of natural gas are representative of the European context and include the impacts of natural gas burned in a boiler with atmospheric burner (non-modulating) and power lower than 100 kW.

Table 2.3.3.2: Input data for the conventional system

Components of the conventional system	**U.M.**	**Quantity**
Pipes	m	25
Pump (40 W)	unit	7.5
Energy sources		
Electricity, low voltage, Italy (including import)	kWh/year	1999
Other information		
Useful life of the system	year	10

Life cycle impact assessment and interpretation

The results of the LCA analysis, shown in Table 2.3.3.3, indicate that the conventional system performs better than the SHC system during the whole life cycle (10 years). In detail, the SHC system has an impact on GER that is 14% higher than the impact of the conventional system. Referring to GWP, very low differences (about 3%) occur between the systems.

Table 2.3.3.3: Energy and environmental impacts of the examined systems.

System	**GER (MJ/FU)**	**GWP (kgCO_{2eq}/FU)**
SHC	2.57E+05	1.50E+04
Conventional	2.25E+05	1.46E+04

Figures 2.3.3.1 and 2.3.3.2 show the contribution of each life cycle step to the total impact on GER and GWP, respectively. It can be observed that the impacts caused during the operation of the SHC system are lower than that of the conventional system, with differences higher than 40% for both impact categories. However, the solar system causes impacts of about an order of magnitude higher during the manufacturing and end-of-life steps. These impacts are generally not counterbalanced by the advantage of using a SHC system during operation. For this reason, looking at the whole life cycle of the systems, it is preferable to install a conventional system.

Looking at the contribution of the different life cycle steps of the conventional system on the total impact, the operation is responsible of about 95% of GER and 88% of GWP, the manufacturing step gives a contribution of about 5% to GER and of about 11% on GWP, while the impact of the end-of-life step is negligible (lower than 0.2%). The conventional chiller is the component of the system that causes the higher impacts during the manufacturing step (about 76% of GER and 93% of GWP). GER and GWP of the end-of-life step are mainly caused by the pipes (about 44% of GER) and the conventional chiller (about 90% of GWP) dismantling. By analysing the contribution of the different life cycle steps to the total impacts of the SHC system, it can be noted that:

- The operation step is the main contributor towards the GER and GWP (about 50%);
- The contribution of the end-of-life step is lower than 2.2%;

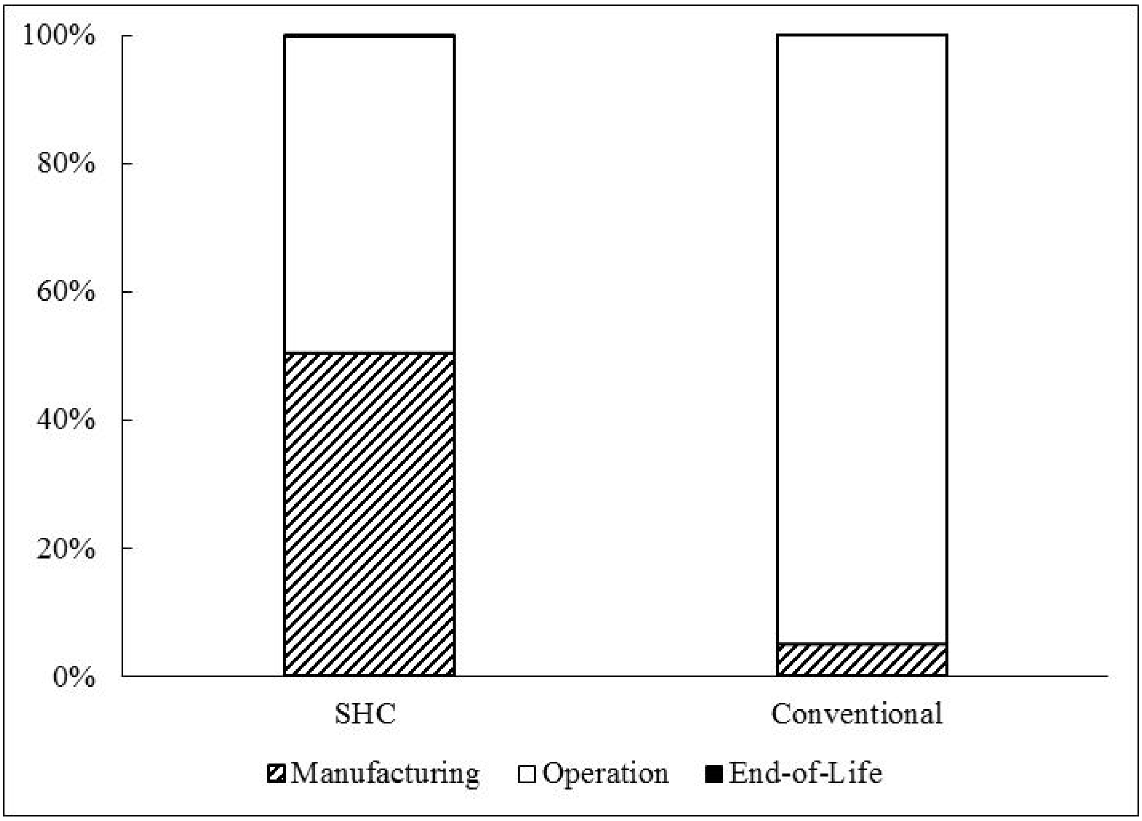


Figure 2.3.3.1 Contribution to GER of each life cycle step

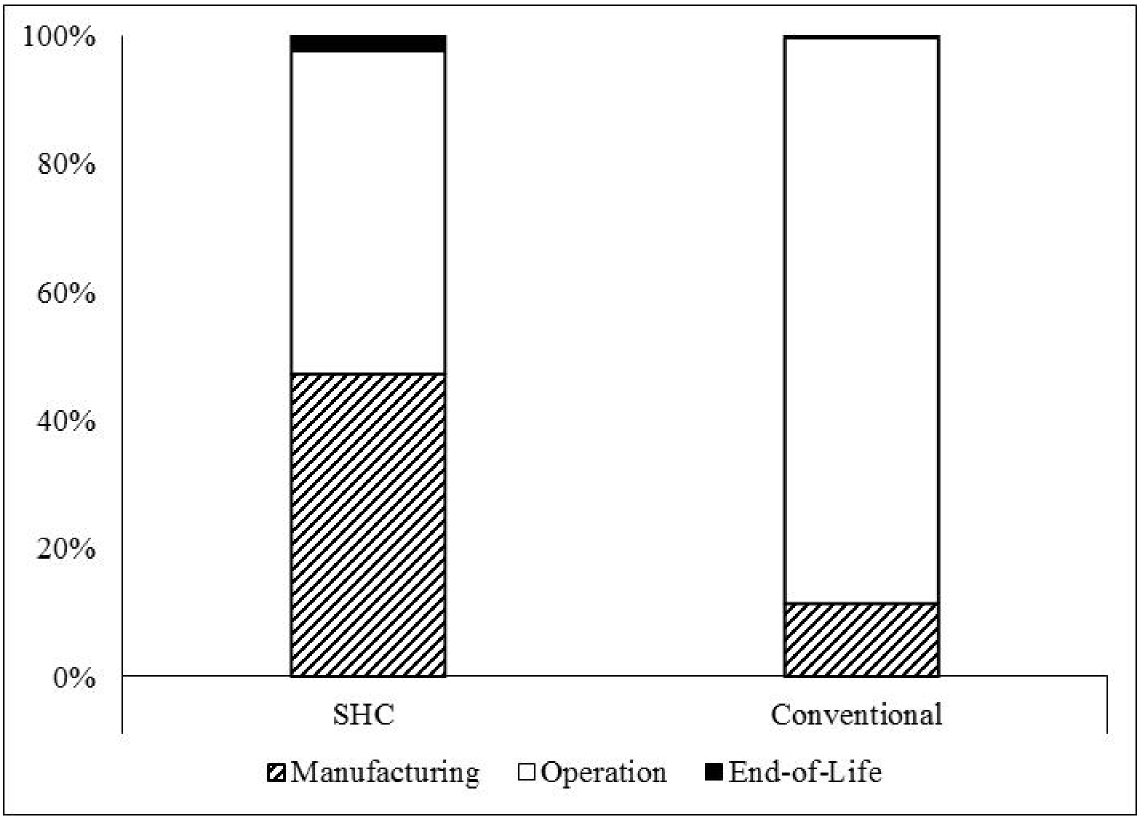


Figure 2.3.3.2 Contribution to GWP of each life cycle step

Focusing on the manufacturing step of the SHC system, the production of solar thermal collectors causes the main impacts both on GER and GWP (about 47%) followed by the adsorption chiller (about 25% of the impacts). The solar thermal collectors are also responsible of the higher impacts during the end-of-life step (about 75% of GER and 45% of GWP). During the operation step the higher impacts (about 70%) are caused by the use of natural gas.

Starting from the LCA results, the EPT, GWP-PT and ERR indices were calculated (Table 2.3.3.4), in order to evaluate the time needed to offset the additional energy consumption and environmental impacts due to the manufacturing and end-of-life of a SHC system in substitution with a conventional one.

EPT and GWP-PT are higher than 10 years, showing that there is not an environmental advantage of installing a SHC system. The values of ERR is about 0.7. This means that the primary energy saved during the useful life of the SHC system slightly overcomes the primary energy consumption due to its manufacture and end-of-life.

Table 2.3.3.4: Energy and environmental payback time indices.

System	EPT (years)	GWP-PT (years)	ERR
SHC	13.66	10.89	0.69

Sensitivity analysis

The analysis of the LCA results highlighted that there is not an environmental benefit of using the SHC system in substitution of the conventional one. The main parameter that influences this result is the useful life of the system, that is too short so that the yearly energy saving and avoided GWP impact due to the use of the solar system can compensate the additional impacts caused by its manufacturing and end-of-life. In order to evaluate if the installation of a SHC system with a useful life higher than 10 years can be convenient from an energy and environmental point of view, a sensitivity analysis has been developed. In detail, a system with a useful life of 15 and 20 years has been analysed. The results of the sensitivity analysis are shown in Figures 2.3.3.3 (GER) and 2.3.3.4 (GWP). From the analysis resulted that the increase in the useful life of the system makes the installation of a SHC system advantageous: the benefit of using a SHC system during operation counterbalances the additional impact generated during the other life cycle steps.

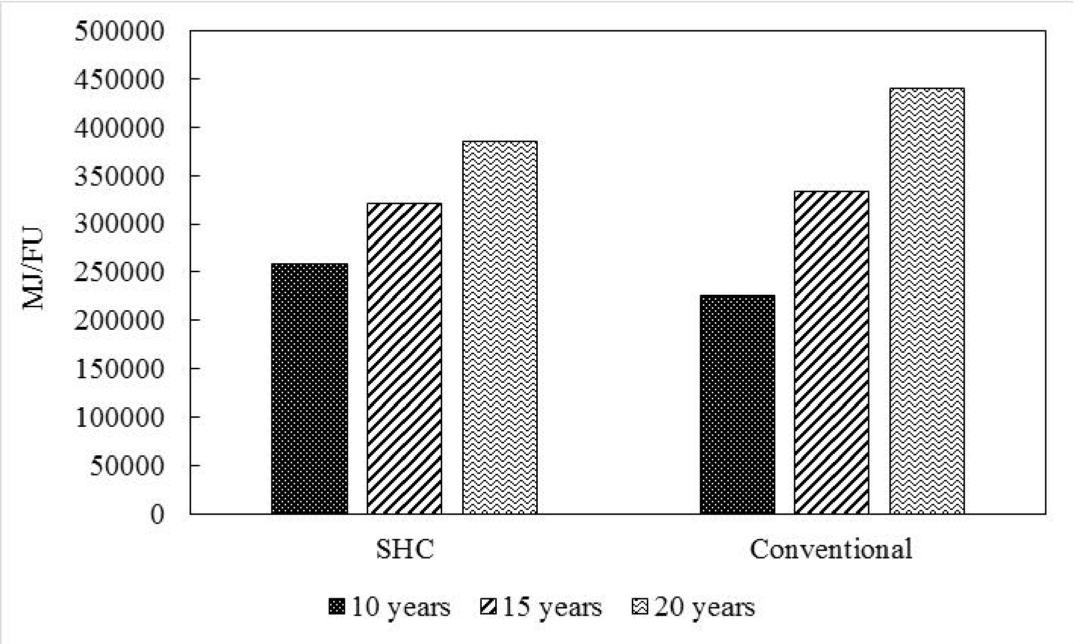


Figure 2.3.3.3: Sensitivity analysis: GER results.

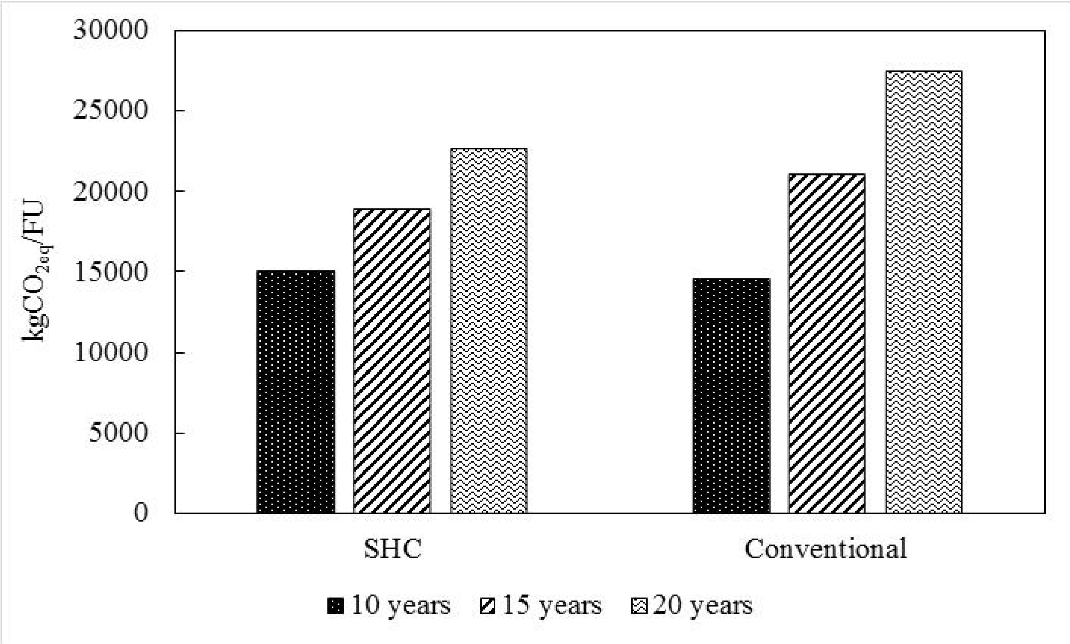


Figure 2.3.3.4: Sensitivity analysis: GWP results.

2.4 Life Cycle Assessment and techno-economic data of a PV – air conditioner manufacturing

2.4.1 The examined system

The examined product is an air conditioner equipped with a photovoltaic plant that produces all the electricity it needs. The main components of the PV – air conditioner system are the PV panels and the air conditioning unit (Figure 2.4.1.1).

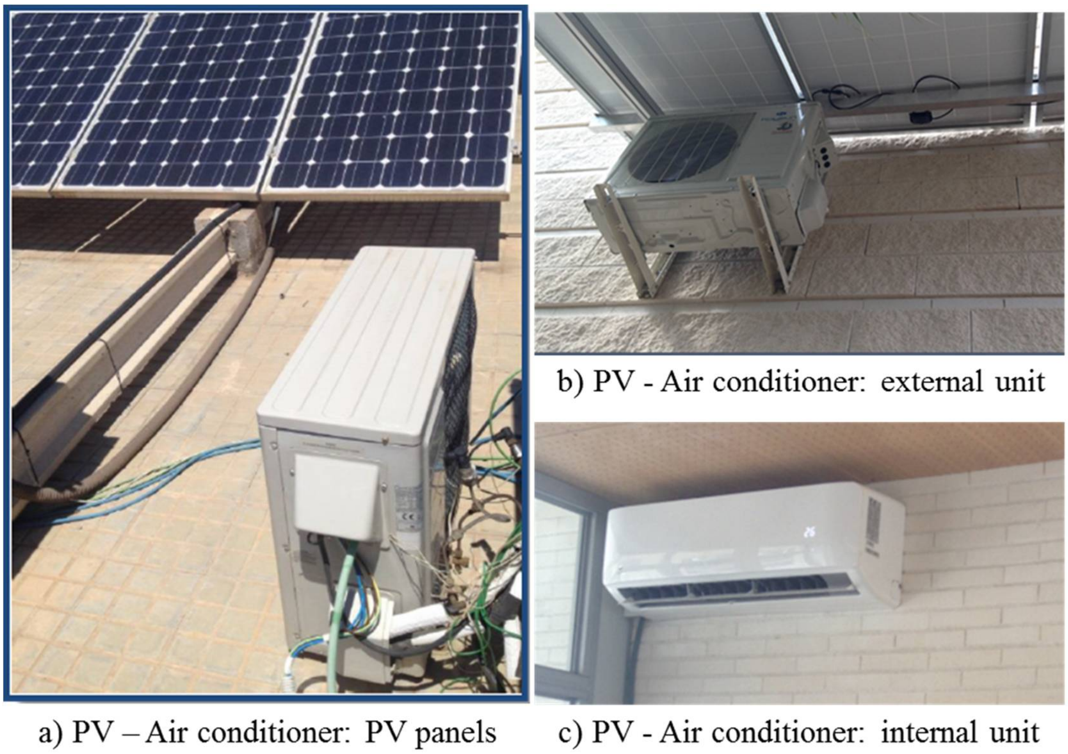


Figure 2.4.1.1: PV – air conditioner system

2.4.2 Techno-economic data

The economic assessment of the system indicates that the real cost of the system in Spain is:

- Air-conditioner: 1800€ + VAT;
- PV: 1200€ + VAT;
- Total 3000€ + VAT

A similar air-conditioner (same efficiency, but without PV connection) has a cost of 1700€ + VAT.

The system has a COP of 3.83, an EER of 5.15 and an efficiency cooling + heating of 4.44.

2.4.3 Life Cycle Assessment

Goal of the study

The goal of the study is to assess the energy and the environmental impacts caused by the manufacturing of a PV – air conditioner unit. The analysis is carried out by applying the Life Cycle Assessment (LCA) methodology in compliance with the international standards of the series ISO 14040 (ISO, 2006a, 2006b).

Functional unit and system boundaries

The selected functional unit (FU) is the PV – air conditioning unit. The system boundaries include the following processes:

- PV manufacturing, including raw material supply, manufacturing/assembly of the main components of the PV panels and of all components needed for the installation, transport of materials to the construction place;
- Air conditioner manufacturing, including the manufacturing and transport of the main components, the energy and water needed for the production process and the emissions of the refrigerant during the production and the scrapping processes.

Impact assessment methodology and impact categories

The following energy and environmental indexes are selected to illustrate the energy and the environmental performance of the examined system:

- Global energy requirement (GER);
- Global warming potential (GWP);
- Ozone depletion (ODP);
- Human toxicity, non-cancer effects (HT-ce);
- Human toxicity, cancer effects (HT-nce);
- Particulate matter (PM);
- Ionizing radiation, HH (IR-hh);
- Ionizing radiation, E;
- Photochemical ozone formation (POFP);
- Acidification (AP);
- Terrestrial eutrophication (T-EU);
- Freshwater eutrophication (F-EU);
- Marine eutrophication (M-EU);
- Freshwater ecotoxicity (F-E);
- Land use (LU);
- Water resource depletion (WRD);
- Mineral, fossil & renewable resource depletion (MFRRD).

The characterisation models used for the impact calculations are the Cumulative Energy Demand (CED) (Frischknecht et al., 2007) method for the energy impacts, and ILCD 2011 Midpoint method for the environmental impacts (European Commission - Joint Research Centre, 2012).

Data quality

The eco-profiles of materials and energy sources used to produce the main components of the analysed FU are based on the Ecoinvent database (Frischknecht et al., 2005; Wernet et al., 2016).

Life Cycle inventory analysis

Data collection

The data needed to assess the energy and environmental impacts of the FU are collected from the PV – air conditioner data sheet provided by the manufacturer.

The PV system consists of three modules made of polycrystalline silicon cells. The modules are connected in parallel. The nominal power of each panel is 235 W and the area 1.67 m^2. The PV modules are covered by a 3.3 mm tempered glass.

The air conditioner system has a cooling power of 3.7 kW and a heating power of 3.8 kW. The Seasonal Energy Efficiency Ratio (SEER) and the Seasonal Coefficient of Performance (SCOP) are, respectively, 7.5 (energy efficiency class A++ in cooling mode) and 4 (energy efficiency class A+ in heating mode). It is assumed that the air – conditioner unit adopt the R134a as refrigerant.

Life cycle impact assessment and interpretation

The GER of the PV – air conditioner manufacturing is 2.60E+04 $MJ_{primary}$ of which 86% is non – renewable primary energy (Table 2.4.3.1). The PV panels manufacturing is responsible for the highest primary energy consumption. In detail, they represent 88% of the GER. Figure 2.4.3.1 shows the contribution of the air conditioner and PV units to the GER, classified in non – renewable and renewable energy.

Table 2.4.3.1: PV – Air conditioner system manufacturing: GER

Primary energy consumption	Air - conditioner	PV panels	Total
Non - renewable ($MJ_{primary}$)	2,85E+03	1,95E+04	2,23E+04
Renewable ($MJ_{primary}$)	1,59E+02	3,52E+03	3,68E+03
Total ($MJ_{primary}$)	3,01E+03	2,30E+04	2,60E+04

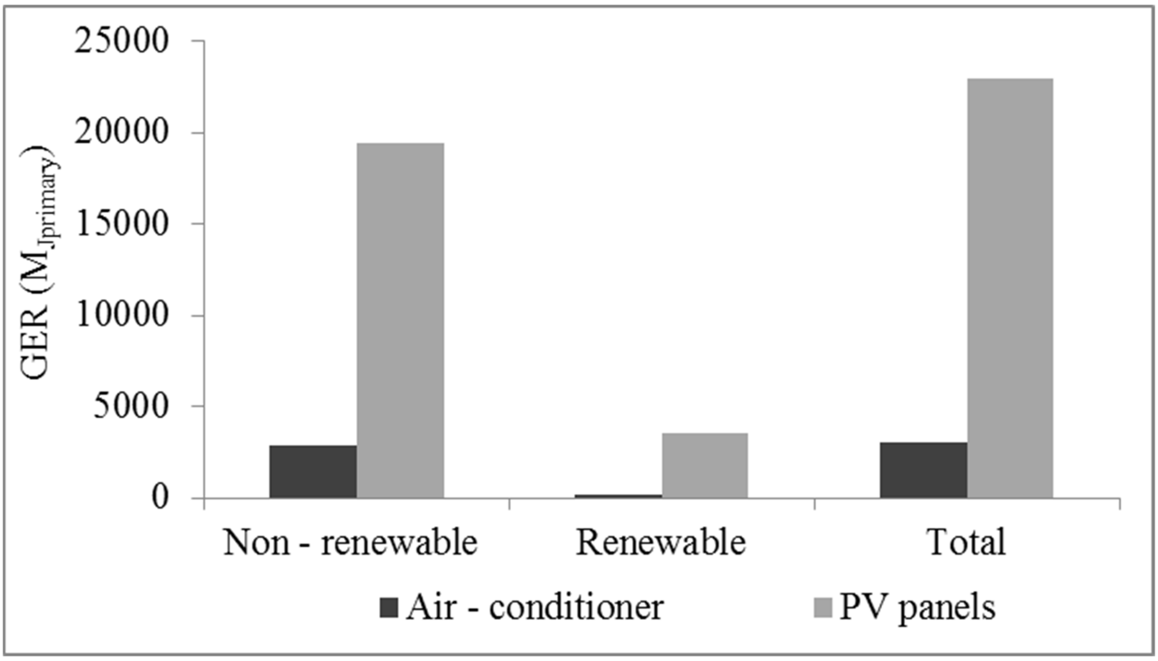


Figure 2.4.3.1: GER processes contribution

The environmental impacts due to the PV – air conditioner manufacturing are shown in Table 2.4.3.2.

The highest impacts are observed for the PV panels in all the examined environmental categories, the only exception is the ODP for which the air conditioner manufacturing contribution is 98%, mainly related to the refrigerant R134a production. The PV panels impact contribution ranges from 2% (ODP) to 96% (WRD) (Figure 2.4.3.2).

As climate change is one of the greatest environmental challenges, a detailed analysis of the processes contribution is carried out with reference to the GWP impact category. The analysis highlights that the direct emission of the refrigerant R134a during the production of the air conditioner unit is responsible for the highest impact (19.6%); the electricity used in the PV panels production process contributes with a percentage of 10.6%. The production process of the refrigerant 134a represents a contribution of 5.8% of the overall GWP. The remaining processes (e.g. primary aluminium production, natural gas and hard coal burned in power plants, the production of the PV cells, etc.), which give a percentage contribution to the GWP impact category lower than 5%, represent 64% of the overall contribution (Figure 2.4.3.3).

Table 2.4.3.2: PV – Air conditioner system manufacturing: Environmental impacts

Impact categories	Air - conditioner	PV panels	Total
GWP (kg CO_{2eq})	6.23E+02	1.24E+03	1.87E+03
ODP (kg CFC-11_{eq})	1.19E-02	2.69E-04	1.21E-02
HT-ce (CTUh)	8.32E-05	1.83E-04	2.66E-04
HT-nce (CTUh)	8.56E-04	1.40E-03	2.26E-03
PM (kg $PM2.5_{eq}$)	1.59E-01	6.05E-01	7.63E-01
IR-hh (kBq U^{235}_{eq})	5.66E+01	3.40E+02	3.96E+02
IR-e (CTUe)	1.71E-04	1.04E-03	1.21E-03
POFP (kg $NMVOC_{eq}$)	5.95E-01	4.54E+00	5.13E+00
AP (molc H^+_{eq})	1.92E+00	6.98E+00	8.90E+00
T-EU (molc N_{eq})	2.05E+00	1.22E+01	1.43E+01
F-EU (kg P_{eq})	4.80E-01	1.02E+00	1.50E+00
M-EU (kg N_{eq})	1.87E-01	1.31E+00	1.50E+00
F-E (CTUe)	1.85E+04	3.47E+04	5.32E+04
LU (kg $C_{deficit}$)	1.71E+02	1.03E+03	1.20E+03
WRD ($m^3 water_{eq}$)	1.75E+02	4.62E+03	4.80E+03
MFRRD ($kgSb_{eq}$)	4.40E-02	5.91E-01	6.35E-01

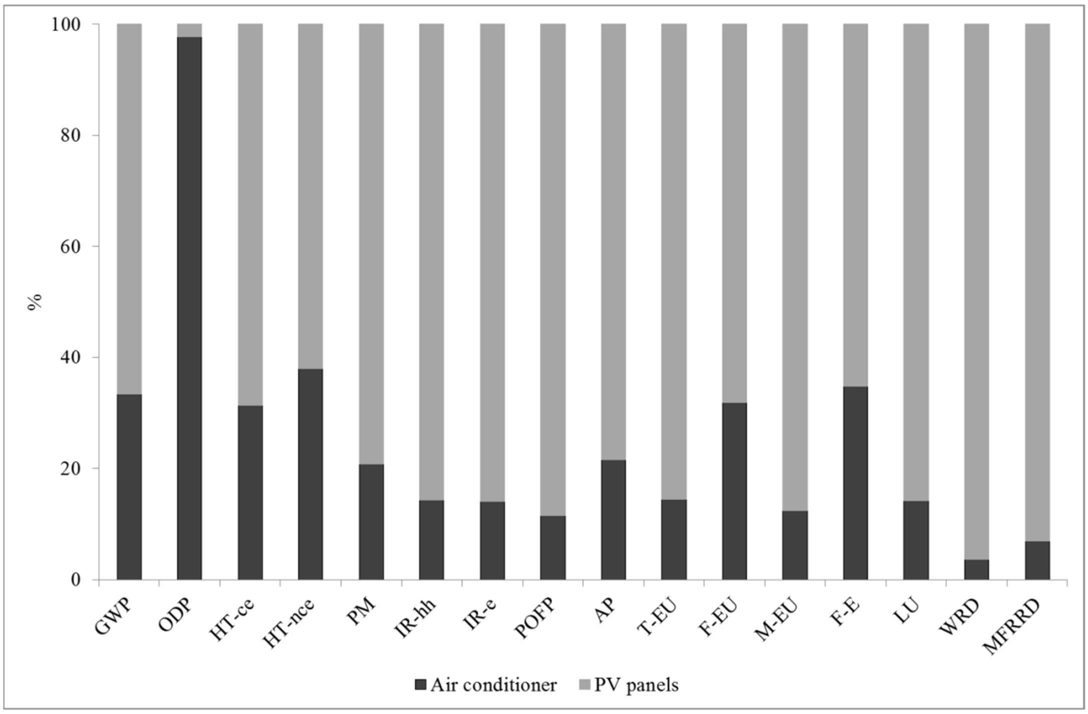


Figure 2.4.3.2: Environmental impacts processes contribution

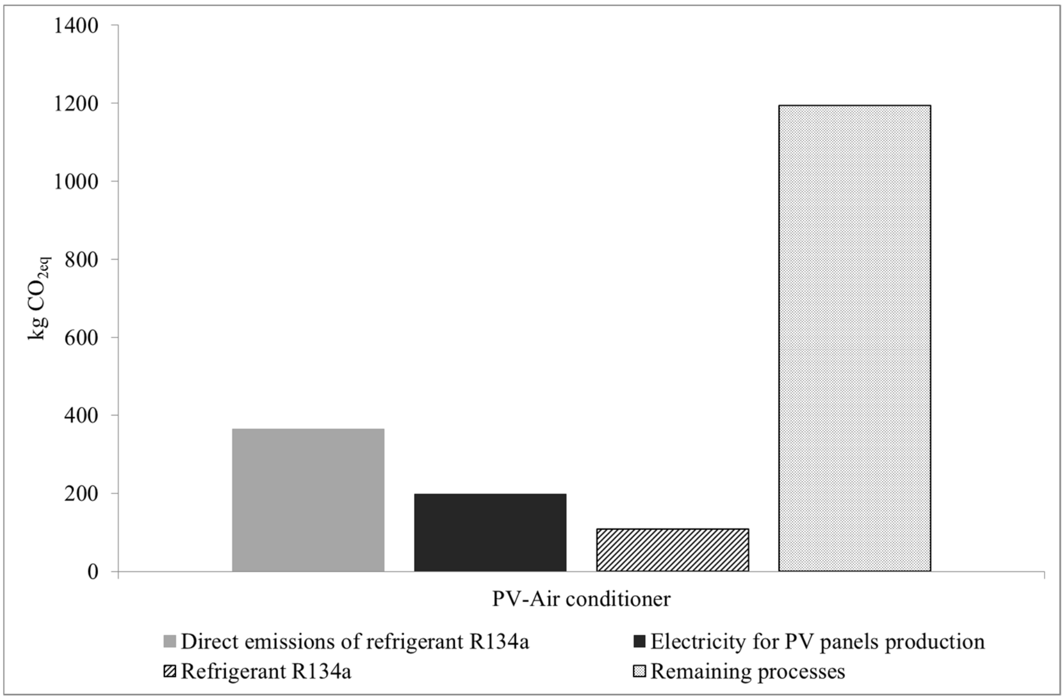


Figure 2.4.3.3: GWP impact processes contribution

2.5 Life Cycle Assessment of a PV – air conditioner manufacturing

2.5.1 The examined system

The examined product is a PV cooling designed to operate by using the electricity produced by a photovoltaic power plant. The main components of the examined PV cooling are the PV system, the heat pump and the chilled water circuit (Figure 2.5.1.1).

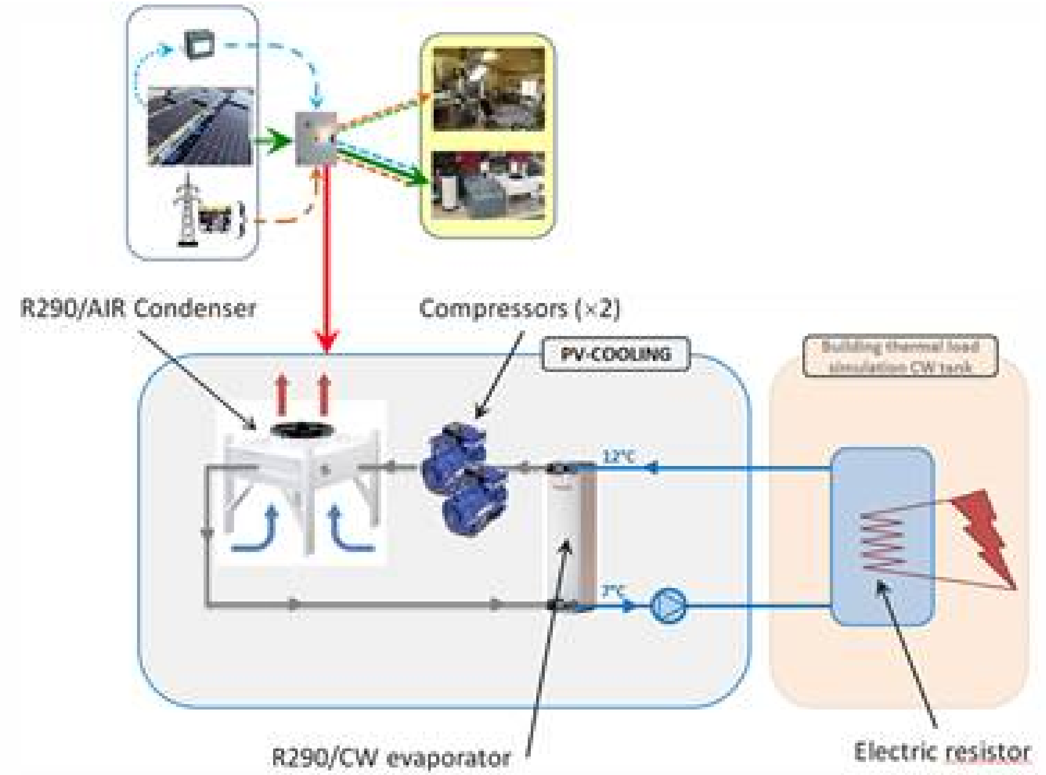


Figure 2.5.1.1: PV – cooling scheme

2.5.2 Life Cycle Assessment

Goal of the study

The goal of the study is to assess the energy and the environmental impacts caused by the manufacturing of a PV cooling system. The analysis is carried out by applying the Life Cycle Assessment (LCA) methodology in compliance with the international standards of series ISO 14040 (ISO, 2006a, 2006b).

Functional unit and system boundaries

The selected functional unit (FU) is the PV cooling system. The system boundaries include the raw material supply, materials production, manufacturing/assembly of the main components of the system, including transportation.

Impact assessment methodology and impact categories

The following energy and environmental indexes are selected to illustrate the energy and the environmental performance of the examined system:

- Global energy requirement (GER);
- Global warming potential (GWP);
- Ozone depletion (ODP);
- Human toxicity, non-cancer effects (HT-ce);
- Human toxicity, cancer effects (HT-nce);
- Particulate matter (PM);
- Ionizing radiation, HH (IR-hh);
- Ionizing radiation, E;
- Photochemical ozone formation (POFP);
- Acidification (AP);
- Terrestrial eutrophication (T-EU);
- Freshwater eutrophication (F-EU);
- Marine eutrophication (M-EU);
- Freshwater ecotoxicity (F-E);
- Land use (LU);
- Water resource depletion (WRD);
- Mineral, fossil & renewable resource depletion (MFRRD)

The characterisation models used for the impact calculations are the Cumulative Energy Demand (CED) (Frischknecht et al., 2007) method for the energy impacts and ILCD 2011 Midpoint method for the environmental impacts (European Commission - Joint Research Centre, 2012).

Data quality

The eco-profiles of materials and energy sources used to produce the main components of the analysed FU are based on the Ecoinvent database (Frischknecht et al., 2005; Wernet et al., 2016).

Life Cycle inventory analysis

Data collection

The data needed to assess the energy and environmental impacts of the FU are collected from the PV – cooling data sheet provided by the manufacturer. The PV system consists in 18 mono-crystalline photovoltaic modules and in a battery energy storage system (BESS). The modules are connected in parallel. The nominal power of each panel is 280 W_p. The overall nominal capacity is 5.04 kW_p. Each panel has an area of 1.62 m^2, a frame made of anodized aluminium and it is covered with a transparent tempered glass of 3.2 mm. The BESS is constituted by four lead acid batteries. The nominal energy capacity is 28.8 kWh.

The heat pump consists in:

- Two semi – hermetically compressor. The cooling power ranges from 2.38 to 5.38 kW. The Coefficient of Performance (COP) is 3.56;

- Refrigerant (Propane, R290);
- Refrigerant tank (2.8 l);
- Filter drier for refrigerant;
- Sight glass for refrigerant circuit;
- Electronic pressure switch;
- Low and high security pressure switch;
- Solenoid valves and coil for solenoid valves;
- An air-cooled condenser (micro-channel type condenser) (Figure 2.5.2.1);
- An evaporator (brazed plate heat exchangers);
- A super-heater (brazed plate heat exchangers);
- Pump with a mass flow ranging from 2 to 12 m^3/h;
- Expansion tank (steel);
- Electronic expansion valve;
- An effective circuit oil, including a filter drier, a sight glass for oil circuit, isolation valves for oil level regulation, a mechanical oil level regulator, an oil tank valve, an oil tank, an oil separator);
- Frame and various panels of the heat pump box.

Figure 2.5.2.1: Condenser

The chilled water circuit (Figure 2.5.2.2) consists in a 1000 l thermal storage tank and in a 200 l thermal storage tank with an electrical resistance to simulate the building loads (Figure 2.5.2.3). Finally, a monitoring system is included to control the performance of the system. The chilled water consists in a mix of water and methyl propylene glycol (30% glycol).

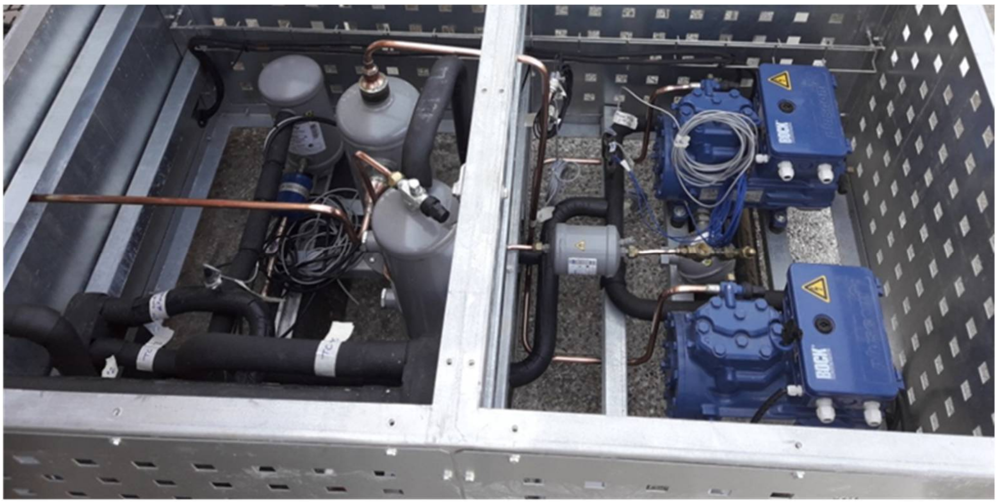


Figure 2.5.2.2: Chilled water circuit

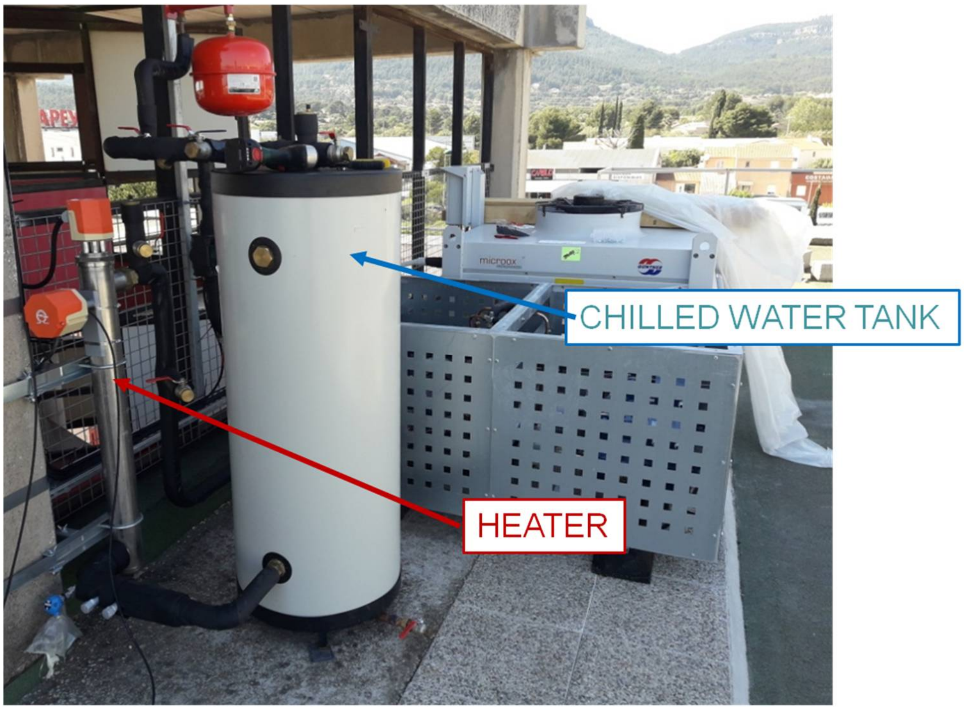


Figure 2.5.2.3: 200 l chiller water tank

Life cycle impact assessment and interpretation

The GER of the PV – cooling unit manufacturing is 2.86E+05 $MJ_{primary}$ of which 88% is non – renewable primary energy. In Table 2.5.2.1 are illustrated the impacts on GER of each component, classified in non – renewable and renewable energy. The PV panels manufacturing and the chilled water circuit are responsible for the highest primary energy consumptions. In detail, they account, respectively, for 71% and 16% of the GER.

Table 2.5.2.1: PV cooling system manufacturing: GER

Primary energy consumption	PV system	BESS	Heat pump	Chilled water circuit	Total
Non - renewable	1.76E+05	2.01E+04	1.55E+04	4.09E+04	2.52E+05

Renewable	2.58E+04	1.05E+03	2.68E+03	3.80E+03	3.33E+04
Total	2.01E+05	2.12E+04	1.82E+04	4.47E+04	2.86E+05

Figure 2.5.2.4 shows the contribution of each component to the GER, classified in non – renewable and renewable energy.

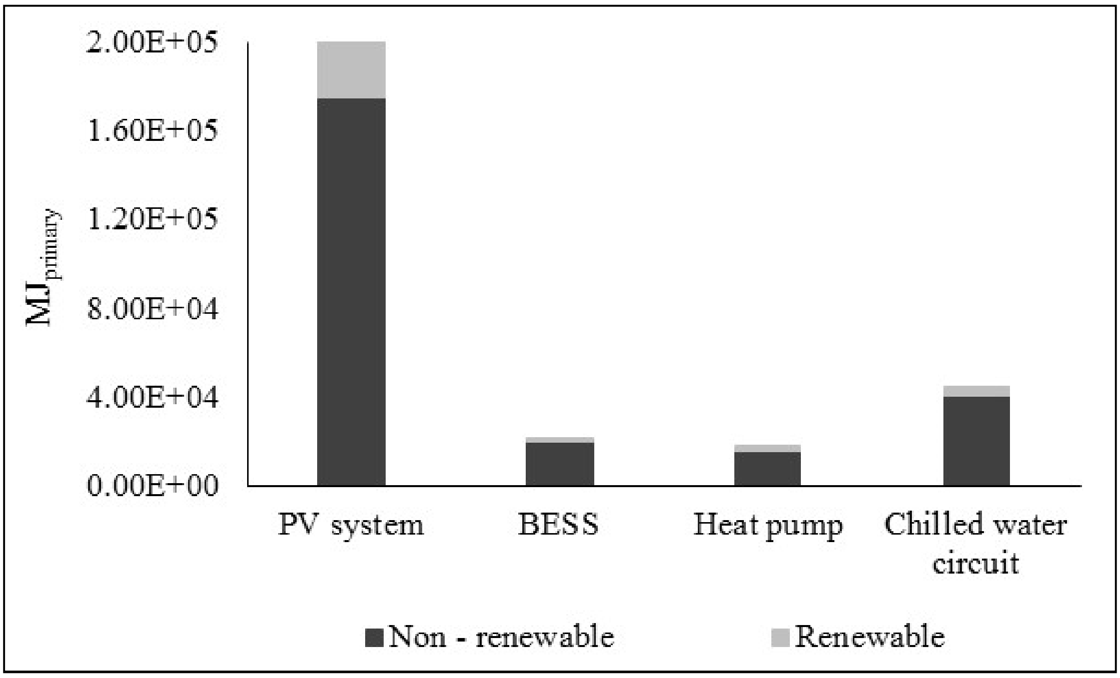


Figure 2.5.2.4: PV cooling components contribution on non-renewable and renewable GER

The environmental impacts due to the PV cooling manufacturing are shown in Table 2.5.2.2.

The PV panels account for the highest impact in all the examined impact categories, the exceptions are the ODP, in which they represent about 12% of the overall impact, and MFRRD, in which they represent about 40% of the overall impact. The contributions of the PV in the other impact categories range from 40.7% (for HT-nce) to 93% (for WRD). The BESS contributions range from a minimum of about 0.9% in ODP up to 50.4% for MFRRD. The heat pump is responsible for the highest contribution to the ODP (about 86%) due to the refrigerant R134a production, used as a proxy for the refrigerant R290. The chilled water circuit contributions range from 0.8% for ODP to 35.6% for HT-nce.

Figure 2.5.2.5 shows the contribution of each component to the examined impact categories.

As climate change is one of the greatest environmental challenges, a detailed analysis of the processes contribution is carried out with reference to the GWP impact category. The analysis highlights that the PV panels are responsible for the highest impact, representing a percentage equal to 74% of the total GWP. The production process of the thermal storage tanks follow with a contribution of about 8%. The ethylene glycol, used in chilled water circuit, and the steel used in different components of the examined system are responsible, respectively, for 4% and 3% of the total impact on GWP. The remaining components, which give a percentage contribution to the GWP impact category lower than 3%, represent 10% of the overall contribution (Figure 2.5.2.6).

Table 2.5.2.2: PV cooling system manufacturing - Environmental impacts

Impact categories	PV	BESS	Heat pump	Chilled water circuit	Total
GWP (kg CO_{2eq})	1.31E+04	9.99E+02	1.42E+03	2.15E+03	1.76E+04
ODP (kg CFC-11_{eq})	1.81E-03	1.36E-04	1.26E-02	1.23E-04	1.46E-02
HT-ce (CTUh)	1.32E-02	3.94E-03	3.12E-03	1.81E-03	2.21E-02
HT-nce (CTUh)	1.52E-03	1.94E-04	6.95E-04	1.33E-03	3.74E-03
PM (kg $PM2.5_{eq}$)	1.42E+01	1.18E+00	2.00E+00	2.26E+00	1.97E+01
IR-hh (kBq $U^{235}{}_{eq}$)	1.47E+03	1.43E+02	1.01E+02	2.47E+02	1.96E+03
IR-e (CTUe)	4.83E-03	4.67E-04	3.44E-04	7.81E-04	6.42E-03
POFP (kg $NMVOC_{eq}$)	4.59E+01	4.09E+00	5.12E+00	7.93E+00	6.31E+01
AP (molc $H^+{}_{eq}$)	9.88E+01	1.09E+01	1.39E+01	1.26E+01	1.36E+02
T-EU (molc N_{eq})	1.35E+02	1.50E+01	1.66E+01	2.35E+01	1.90E+02
F-EU (kg P_{eq})	1.10E+01	2.64E+00	1.86E+00	1.28E+00	1.68E+01
M-EU (kg N_{eq})	1.53E+01	1.82E+00	2.28E+00	2.15E+00	2.16E+01
F-E (CTUe)	1.20E+06	9.71E+04	8.10E+04	5.27E+04	1.43E+06
LU (kg $C_{deficit}$)	1.39E+04	2.71E+03	1.99E+03	4.37E+03	2.30E+04
WRD ($m^3 water_{eq}$)	1.20E+02	2.71E+00	-2.21E+00	8.38E+00	1.29E+02
MFRRD ($kgSb_{eq}$)	3.79E+00	4.88E+00	6.01E-01	4.09E-01	9.68E+00

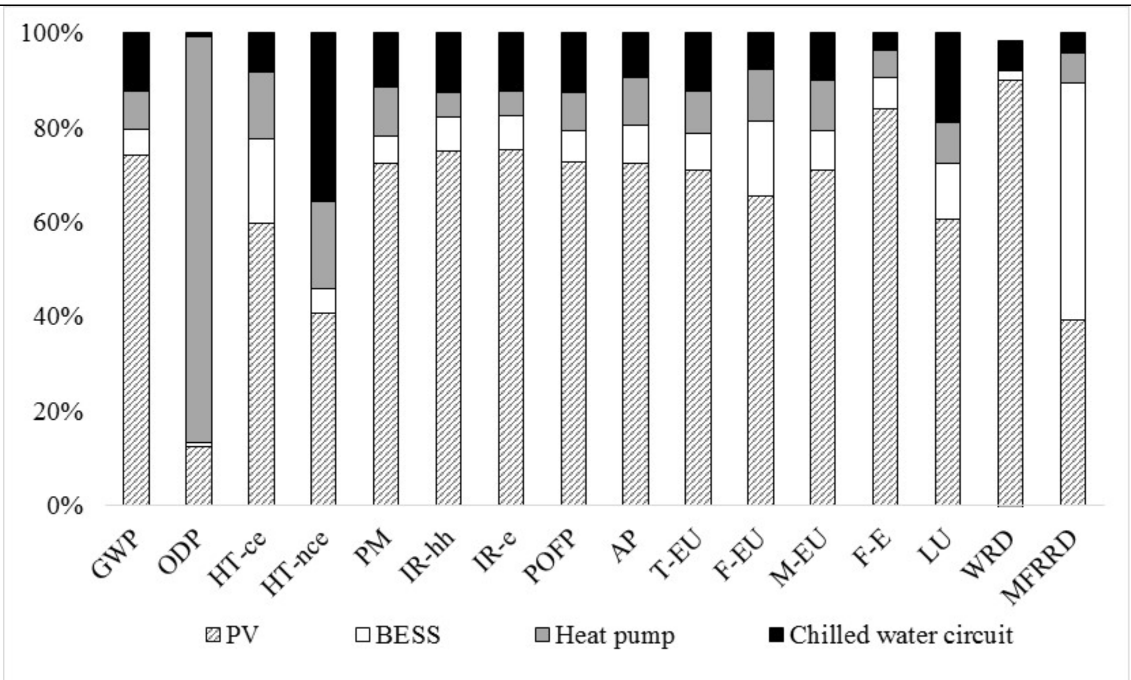


Figure 2.5.2.5: Environmental impacts processes contribution

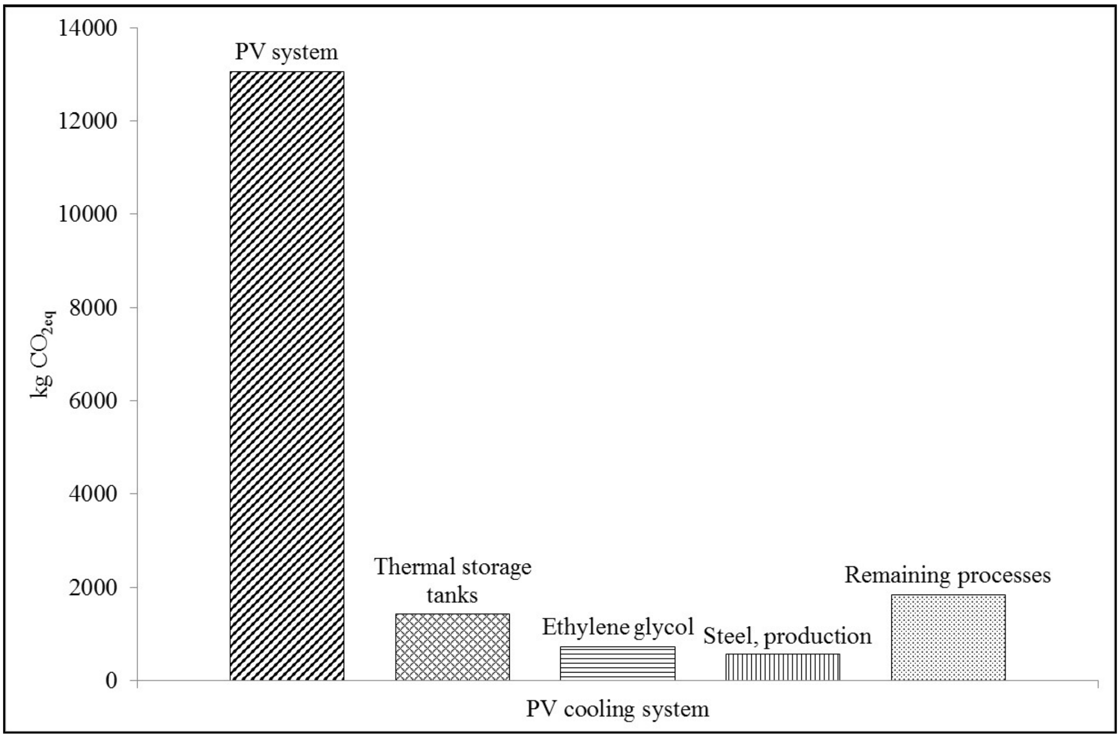


Figure 2.5.2.6: GWP impact processes contribution

2.6 Life Cycle Assessment of an Air handling unit desiccant cooling (AHU-DEC)

2.6.1 The examined system

The examined system is an Air Handling Unit Desiccant Cooling (AHU-DEC) equipped with a hybrid photovoltaic/thermal (PV/T) collectors, used for building air conditioning. The total flow rate delivered to the building is 2,000 m^3/h; the maximum cooling power is about 20 kW. The system is installed on the rooftop of the Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici of the University of Palermo.

Figure 2.6.1.1: Solar assisted AHU-DEC

A hybrid PV/T plant provides both electrical and thermal energy used in AHU-DEC unit. The system consists in a building integrated plant mounted on a supporting steel structure (Figure 2.6.1.2) with a surface of 39 m^2. The PV/T plant covers an area of 38 m^2 and consists in 19 panels.

Figure 2.6.1.2: Hybrid photovoltaic/thermal (PV/T) collectors

2.6.2 Life Cycle Assessment

Goal of the study

The goal of the analysis is the assessment of energy and environmental performances of the solar assisted AHU-DEC described above and the evaluation of the contribution of each component to the total impact. The study was carried out by applying the LCA methodology in compliance with the international standards of series ISO 14040 (ISO, 14040, 2006; ISO 14044, 2006).

Functional unit and system boundaries

The functional unit is the system composed by a solar assisted AHU-DEC plant able to provide 2,000 m^3/h of conditioned air and characterized by a cooling capacity of 20 kW.

The system boundaries include the following life cycle steps:

- Raw materials extraction;
- Production of plant's components;
- End-of-life.

The use phase, the transport of the plant components from their production site to the site of operation, the transport from the site of operation to the disposal site, the installation and maintenance were not taken into account.

For the end-of-life step of the hybrid photovoltaic/thermal (PV/T) collectors, the recycling of the following components was included: aluminium, steel, galvanized steel, galvanized iron, air duct system are been considered. The end-of-life of glass, rock wool and PV panels was modelled considering the final disposal in landfill.

The end-of-life step of AHU-DEC included the recycling of PVC, stainless steel, polypropylene, galvanized steel, aluminium, polyurethane, high density polyurethane, carbon steel, silicone, polyester (filter); the landfill disposal was selected as final treatment for fiberglass, brass, nylon reinforced with glass fibers, copper, protective coating, glass wool, glass fiber paper and incineration for EPDM. The end-of-life of silica gel grains was not modelled due the lack of reliable data.

Impact assessment methodology and impact categories

The energy and environmental impacts were estimated by using Cumulative Energy Demand (Frischknecht et al., 2007) and ILCD 2011 Midpoint methods (European Commission – Joint Research Centre, 2012), respectively. The following impact categories were calculated:

- Non-renewable energy consumption;
- Renewable energy consumption;
- Climate change;
- Ozone depletion;
- Human toxicity, cancer effects;
- Human toxicity, non-cancer effects;
- Particulate matter;
- Ionizing radiation (Human Health);
- Ionizing radiation Ecosystem (interim);
- Photochemical ozone formation;
- Acidification;
- Terrestrial eutrophication;
- Freshwater eutrophication;
- Marine eutrophication;
- Freshwater eco-toxicity;
- Land use;
- Water resource depletion;
- Mineral, fossil and renewable resource depletion.

Data quality

The study is based to primary and secondary data. Primary data were collected through direct measurement of the size and mass of the system components and through information obtained from the manufacturers. Secondary data, related to eco-profile of materials and energy resources u were taken from the environmental database Ecoinvent (Frischknecht et al., 2005; Wernet et al., 2016).

Life Cycle inventory analysis

Data collection

For data collection the plant has been divided in the following sub-components:

- Hybrid PV/T system
    - Steel materials;
    - Iron galvanized materials;
    - Aluminium materials;
    - Sandwich panels;
    - Aluminium sheet with covering in TiNOX
    - PV modules;
    - Special pieces in galvanized steel;
    - Air ducts system;

    - Painting;
    - Glass cover;
- AHU-DEC
    - Cooling tower;
    - Pipes and fittings;
    - Structure;
    - Adsorption beds;
    - Adsorption beds - valves;
    - Openings for the air inlet - adsorption beds;
    - Air ventilation channel;
    - Heat exchanger;
    - Fan;
    - Servo-motors;
    - Shut-off damper;
    - Power cables;
    - Electrical panel.

Table 2.6.2.1 and 2.6.2.2 shows the main materials of the hybrid PV/T system and of the AHU-DEC, respectively.

Table 2.6.2.1: Main materials of the hybrid PV/T system

Material	Quantity
Steel	2,238.7 kg
Galvanized steel	682.4 kg
Galvanized iron	410.4 kg
Aluminium	309.4 kg
Rock wool	304
PV panels	38 m^2
Expanded polystyrene	38.1 kg
Glass	390 kg

Table 2.6.2.2: Main materials of the AHU-DEC system

Material	Quantity (kg)
Fiberglass	53
PVC	24.58
Brass	20.6
Galvanized steel	613
Zinc	3.6
Aluminium	328
Copper	44.8
Polyurethane	48.7
Silica gel	130
Other plastics	7
Stainless steel	23.2

Life cycle impact assessment

The energy impact of the manufacturing and end-of-life steps of the investigated system is shown in Table 2.6.2.3. GER is 5.2E+05 MJ, of which 86% is from non-renewable energy sources. The hybrid PV/T plant contributes about 76% of GER.

Focusing on the hybrid PV/T system, the manufacturing phase represents about 81% of GER, whereas in AHU-DEC about 88%. A detailed analysis of the manufacturing of the two components of the plant is showed in Table 2.6.2.4. An analysis of the results highlights that a relevant share of GER is caused by steel materials manufacturing (31.5%), followed by PV panels (15%), HAU-DEC structure (11%) and aluminium materials (9.4%).

Table 2.6.2.3: Global Energy Requirement of the examined system

Component	Non-renewable primary energy (MJ)	Renewable primary energy (MJ)	GER (MJ)
Hybrid PV/T plant			
Manufacturing	2.8E+05	4.3E+04	3.2E+05
End-of-life	5.9E+04	1.4E+04	7.4E+04
Sub-total (MJ)	**3.4E+05**	**5.8E+04**	**3.9E+05**
HAU-DEC			
Manufacturing	9.4E+04	1.4E+04	1.1E+05
End-of-life	1.4E+04	4.8E+02	1.5E+04
Sub-total (MJ)	**1.1E+05**	**1.5E+04**	**1.2E+05**
Total (MJ)	**4.5E+05**	**7.2E+04**	**5.2E+05**

Table 2.6.2.4: Manufacturing step –Contribution analysis on the energy impact

Component	Non-renewable primary energy (MJ)	Renewable primary energy (MJ)	GER (MJ)
Hybrid PV/T plant			
Steel materials	1.2E+05	1.9E+04	1.4E+05
Aluminium materials	3.3E+04	7.0E+03	4.0E+04
Iron galvanized materials	1.0E+04	2.3E+02	1.0E+04
PV panels	5.3E+04	1.1E+04	6.4E+04
Sandwich panels	2.6E+04	1.4E+03	2.7E+04
Air duct system	3.0E+04	4.3E+03	3.4E+04
Tinox	1.6E+03	3.2E+02	1.9E+03
Painting	2.0E+03	8.6E+01	2.0E+03
Glass cover	5.6E+03	1.9E+02	5.8E+03
HAU-DEC			
Openings for the air inlet - Adsorption bed	8.1E+03	1.3E+03	9.4E+03
Air ventilation channel	1.6E+04	2.5E+03	1.8E+04
Adsorption bed	5.9E+03	1.1E+03	7.0E+03
Packaged wet heat exchanger	8.9E+03	1.6E+03	1.0E+04
Shut-off damper	1.1E+03	1.7E+02	1.2E+03
Servo-motors	2.0E+02	2.4E+01	2.2E+02
HAU-DEC structure	4.0E+04	6.7E+03	4.7E+04
Cooling tower	5.6E+03	2.7E+02	5.9E+03
Pipes and fittings	4.9E+03	2.3E+02	5.1E+03
Adsorption bed - valves	2.3E+03	3.4E+02	2.6E+03
Fan	7.5E+02	9.3E+01	8.5E+02
Power cables	7.7E+02	3.8E+01	8.1E+02

Focusing on the hybrid PV/T manufacturing, a relevant share of GER (approximately 42%) is caused by steel materials manufacturing. PV panels, aluminium materials, air duct system and sandwich panels contribute for 20%, 12.6%, 10.6% and 8.5%, respectively. Contribution to GER lower than 3.5% is caused by the other components.

With reference to AHU-DEC system the largest impacts are caused by structure, air ventilation channel, packaged wet heat exchanger and openings for the air inlet – adsorption bed. These components represent overall about 85% of the GER.

The environmental impacts of the system are detailed in Table 2.6.2.5. From the analysis of result it can be observed that hybrid PV/T system account for more than 57% of the impacts for all categories examined. Focusing on GWP, the total impact is 3.0E+04 kg CO_{2eq}, of which about 76% is caused by the hybrid PV/T plant.

Table 2.6.2.5: Environmental impacts of the examined system

Impact categories	Hybrid PV/T system	AHU - DEC	Total
Climate change (kg CO_{2eq})	2.3E+04	7.3E+03	3.0E+04
Ozone depletion (kg CFC-11_{eq})	2.0E-03	4.5E-04	2.5E-03
Human toxicity, cancer effects (CTUh)	1.2E-02	3.4E-03	1.6E-02
Human toxicity, non-cancer effects (CTUh)	1.3E-02	9.7E-03	2.3E-02
Particulate matter (kg $PM_{2.5eq}$)	1.8E+01	6.2E+00	2.4E+01
Ionizing radiation HH (kBq $U235_{eq}$)	4.1E+03	1.3E+03	5.4E+03
Ionizing radiation E (interim) (CTUe)	1.2E-02	4.1E-03	1.7E-02
Photochemical ozone formation (kg $NMVOC_{eq}$)	7.1E+01	2.2E+01	9.3E+01
Acidification (mol H^+_{eq})	1.3E+02	5.1E+01	1.8E+02
Terrestrial eutrophication (mol N_{eq})	2.3E+02	7.6E+01	3.1E+02
Freshwater eutrophication (kg P_{eq})	8.9E+00	5.9E+00	1.5E+01
Marine eutrophication (kg N_{eq})	2.2E+01	7.3E+00	3.0E+01
Freshwater ecotoxicity (CTUe)	3.7E+05	2.4E+05	6.1E+05
Land use (kg $C_{deficit}$)	1.9E+04	6.3E+03	2.5E+04
Water resource depletion (m^3 $water_{eq}$)	6.7E+04	2.3E+04	9.0E+04
Mineral, fossil & ren resource depletion (kg Sb_{eq})	6.7E+00	1.6E+00	8.3E+00

Tables 2.6.2.6 and 2.6.2.7 summarize the environmental impacts of the hybrid PV/T and AHU-DEC systems, respectively. In both systems, the manufacturing phase account for more than 80% in all examined environmental impact categories. The end-of-life gives a non-negligible impact for the following impact categories: climate change, ozone depletion, photochemical ozone formation, acidification and terrestrial and marine eutrophication.

Table 2.6.2.6: Environmental impacts of the hybrid PV/T system

Impact categories	Manufacturing	End of life
Climate change (kg CO_{2eq})	1.9E+04	4.2E+03
Ozone depletion (kg CFC-11_{eq})	1.8E-03	2.7E-04
Human toxicity, cancer effects (CTUh)	1.2E-02	1.3E-04
Human toxicity, non-cancer effects (CTUh)	1.3E-02	4.7E-04
Particulate matter (kg $PM_{2.5eq}$)	1.7E+01	7.1E-01
Ionizing radiation HH (kBq $U235_{eq}$)	4.1E+03	7.8E-01
Ionizing radiation E (interim) (CTUe)	1.2E-02	2.1E-06
Photochemical ozone formation (kg $NMVOC_{eq}$)	5.8E+01	1.3E+01
Acidification (mol H^{+}_{eq})	1.1E+02	2.1E+01
Terrestrial eutrophication (mol N_{eq})	1.9E+02	4.0E+01
Freshwater eutrophication (kg P_{eq})	8.9E+00	5.5E-02
Marine eutrophication (kg N_{eq})	1.9E+01	3.7E+00
Freshwater ecotoxicity (CTUe)	3.7E+05	2.4E+03
Land use (kg $C_{deficit}$)	1.9E+04	1.3E+02
Water resource depletion (m^3 $water_{eq}$)	6.7E+04	8.4E+00
Mineral, fossil & ren resource depletion (kg Sb_{eq})	6.7E+00	1.5E-04

Table 2.6.2.7: Environmental impacts of the AHU-DEC system

Impact categories	**Manufacturing**	**End of life**
Climate change (kg CO_{2eq})	6.3E+03	9.5E+02
Ozone depletion (kg CFC-11_{eq})	3.6E-04	8.8E-05
Human toxicity, cancer effects (CTUh)	3.4E-03	2.6E-05
Human toxicity, non-cancer effects (CTUh)	9.7E-03	9.3E-05
Particulate matter (kg $PM_{2.5eq}$)	6.1E+00	1.8E-01
Ionizing radiation HH (kBq $U235_{eq}$)	1.3E+03	6.1E-02
Ionizing radiation E (interim) (CTUe)	4.1E-03	1.9E-07
Photochemical ozone formation (kg $NMVOC_{eq}$)	1.9E+01	2.9E+00
Acidification (mol H^{+}_{eq})	4.6E+01	5.0E+00
Terrestrial eutrophication (mol N_{eq})	6.7E+01	8.9E+00
Freshwater eutrophication (kg P_{eq})	5.9E+00	1.1E-02
Marine eutrophication (kg N_{eq})	6.5E+00	8.2E-01
Freshwater ecotoxicity (CTUe)	2.4E+05	5.0E+02
Land use (kg $C_{deficit}$)	6.3E+03	1.2E+01
Water resource depletion (m^3 $water_{eq}$)	2.3E+04	1.4E+00
Mineral, fossil & ren resource depletion (kg Sb_{eq})	1.6E+00	2.1E-05

Detailed analyses of the impacts related to the manufacturing stage are shown in the Figures 2.6.2.1, 2.6.2.2, 2.6.2.3 and 2.6.2.4. In detail, Figure 2.6.2.1 shows the incidence of each component to the total GWP of PV/T plant. The highest impact is caused by steel materials manufacture (about 43%). PV panels, aluminium materials, air duct system and sandwich panels account for 18%, 13.6%, 10.3% and 8.8%, respectively. The lowest impact is caused by painting manufacture (0.5%).

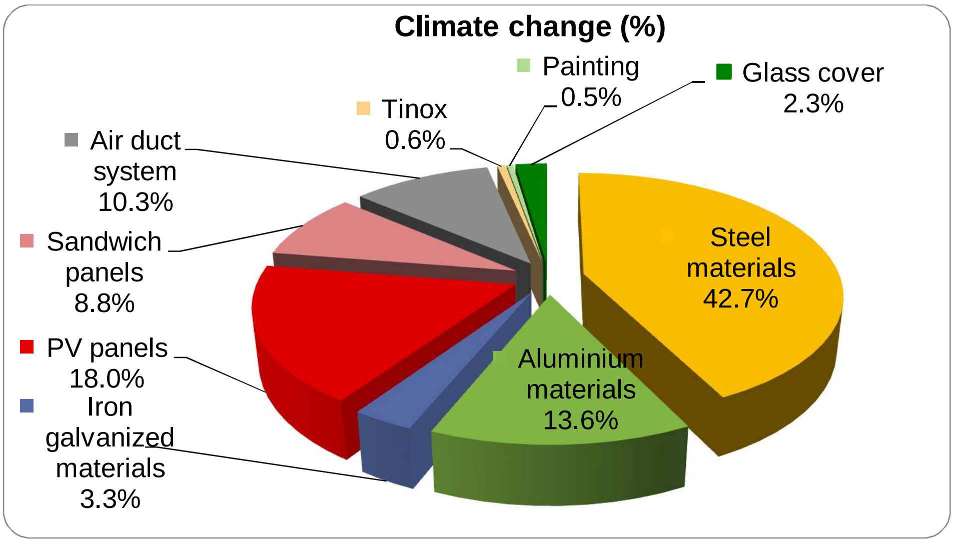


Figure 2.6.2.1: Contribution of each component of the PV/T system to the GWP (%)

The contribution of each hybrid PV/T component to other environmental impacts is shown in Figure 2.6.2.2. The results indicate that steel materials are the main responsible of the impacts for all the examined impact categories with the exception of "Ozone depletion", mainly caused by the PV panels. The contribution to impacts of the other system components is detailed in the following: aluminium materials from 0.4% (Mineral, fossil and renewable resource depletion) to 16% (Ionizing radiation – human health); PV panels from 2.2% (Human toxicity, cancer effects) to 53% (Ozone depletion); sandwich panel from 2.6% (Water resource depletion) to 10.6% (Freshwater eutrophication); Air duct system from 5.5% (Ozone depletion) to 14.1% (Mineral, fossil and renewable resource depletion. Iron galvanized materials is characterized by the highest impact in Human toxicity (9.5% cancer effect, 8.8 non-cancer effects), the other components contribute for less than 5.4% in all impact categories.

Figure 2.6.2.3 shows the contribution of each component of the AHU-DEC to the total impact on GWP. The highest contribution is related to structure manufacturing (44.6%), while the lowest to servo-motors manufacture (0.2%).

Figure 2.6.2.4 reports a contribution analysis for the other impact categories: the AHU-DEC structure manufacture is responsible for the greatest contribution in almost all impact categories examined. The incidence varies from 16.5% (Human toxicity, non-cancer effects) to 51.5% (Mineral, fossil and renewable resource depletion). Adsorption beds contribute from 6.7% (Climate change) to 41% (Human toxicity, non-cancer effects), packaged wet heat exchanger from 5.5% (Human toxicity, non-cancer effects) to 11.3% (Ozone depletion), air ventilation channel from 1% (Mineral, fossil and renewable resource depletion) to 17% (Ionizing radiation, human health), openings for the air inlet in adsorption bed from 4.3% (Human toxicity, non-cancer effects) to 17.4% (Mineral, fossil and renewable resource depletion), pipes and fittings from 1% (Water resource depletion) to 16% (Human toxicity, non-cancer effects) and cooling tower from 1.5% (Water resource depletion) to 7% (Ozone depletion). The other components account for less than 6% in all impact categories examined, in particular shut-off damper, servo-motors and fan have a negligible impact.

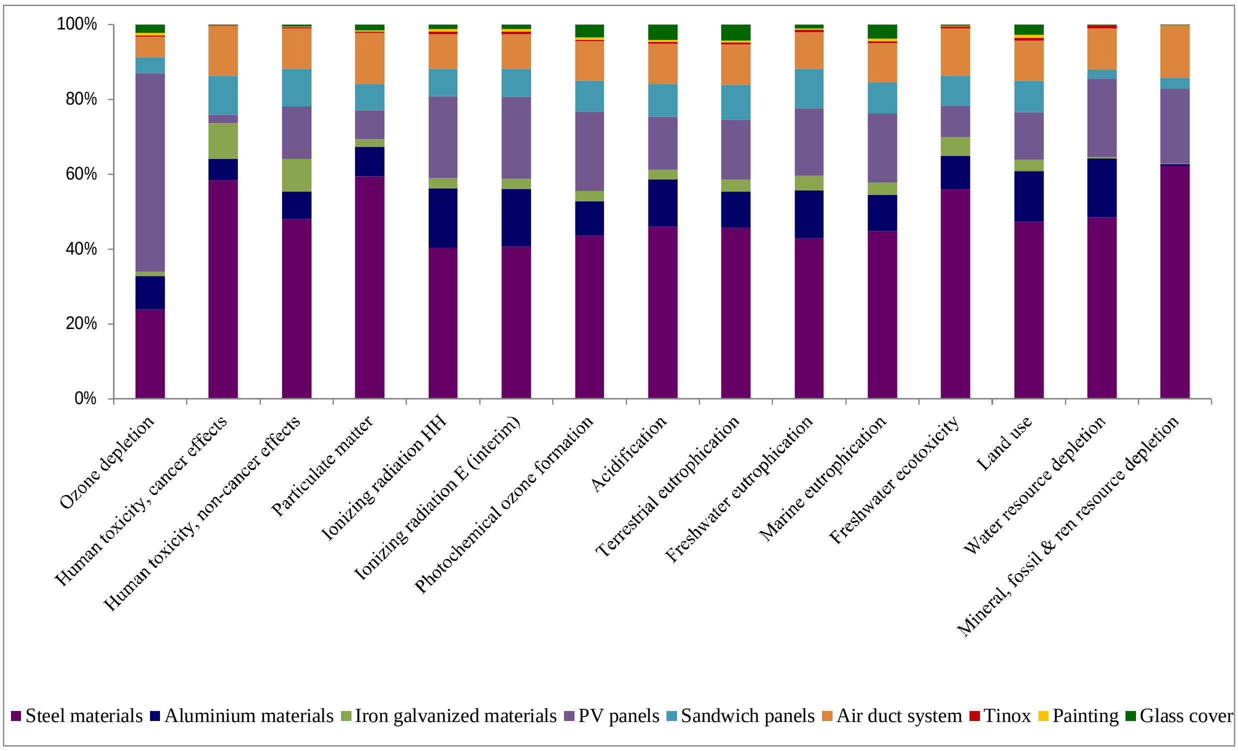


Figure 2.6.2.2: Contribution of each component of the PV/T system to the environmental impact (%)

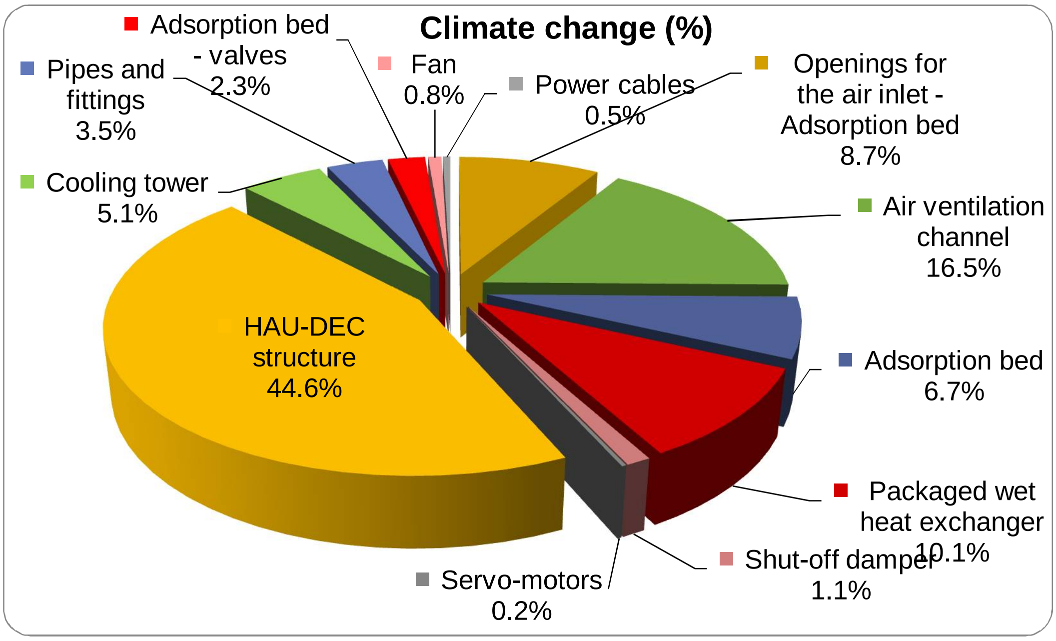


Figure 2.6.2.3: Contribution of each component of the AHU-DEC system to the GWP (%)

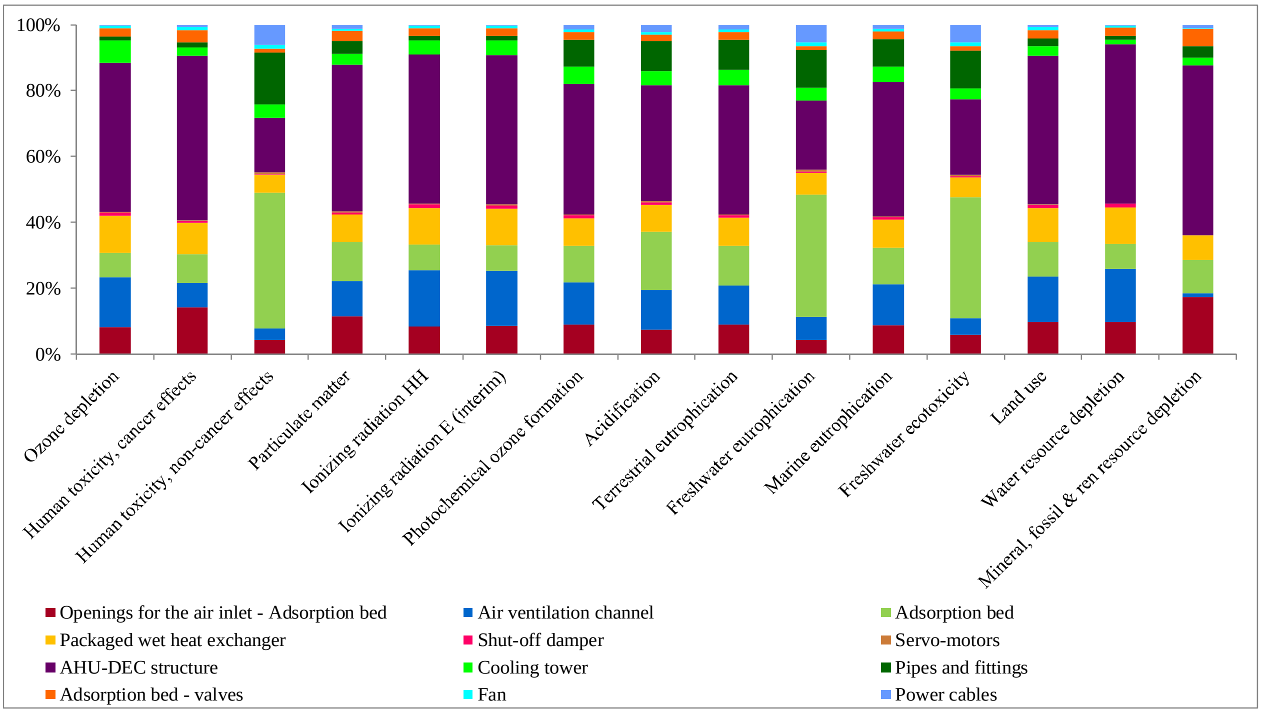


Figure 2.6.2.4: Contribution of each component of the AHU-DEC system to the environmental impact (%)

3. Activity A5-2

The main goal of this activity is to identify a set of Key Performance Indicators (KPIs) and a quality labeling scheme to characterize the market available and the new generation solar cooling systems.

3.1 Definition of KPIs

The definition of KPIs has been based on the three pillars of sustainability (economy, energy/environment, society). In addition, indicators on the technical features of the systems have been identified.

The selected KPIs include:

- Energy indicators:
  - Global Energy Requirement (GER);
  - Energy Payback Time (EPT);
  - Energy Return Ratio (ERR);
- Environmental indicators:
  - Global Warming Potential (GWP);
  - Acidification Potential (AP);
  - Eutrophication Potential (EP);
  - Ozone Depletion Potential (ODP);
  - Photochemical Ozone Creation Potential (POCP);
  - GWP Payback Time (GWP-PT);
- Economic indicators:
  - Money savings during the operation (MSDO);
  - Initial cost ratio (ICR);
  - Operation/maintenance costs ratio (OMC);
  - Payback period (PP);
- Social indicators:
  - Customer satisfaction (CS);
  - Ease of use of the system (EUS);
- Technical indicators:
  - Useful life of the system (ULS);
  - Thermal performance coefficient of the ab/adsorption machine (COP_{th});
  - Solar Electric Performance Coefficient of the system ($COP_{Elec\text{-}sol}$);
  - Reliability of the system (RS).

3.1.1 Energy KPI

KEY PERFORMANCE INDICATOR

Key performance indicator name: Global Energy Requirement (GER)

Typology (economic, energy or environmental, social, technical): Energy indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): MJ

Description: GER represents the entire (renewable and non-renewable) energy demand, valued as primary energy, which arises in connection with the manufacturing, use and disposal of an economic good (product or service)

Performance target: Percentage reduction of GER during the life cycle of the system (to be fixed case by case)

Measurement process: The KPI can be calculated following a life cycle approach with the formula:

$$GER = GER_M + GER_U + GER_{RD}$$

where:

GER_M is the primary energy consumed during the manufacture (including energy and raw materials supply) of a product or a service;

GER_U is the primary energy consumed during the use of a product or a service;

GER_{RD} is the primary energy consumed during the end-of-life of a product or a service (recycling or disposal).

KEY PERFORMANCE INDICATOR

Key performance indicator name: Energy Payback Time (EPT)

Typology (economic, energy or environmental, social, technical): Energy indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): Years

Description: EPT is defined as the time during which the SHC system must work to harvest the additional primary energy required for its manufacturing and end-of-life, if compared with a conventional system. The harvested energy is considered as net of the energy expenditure for the system operation

Performance target: EPT lower than the useful life of the system

Measurement process: The KPI can be calculated with the formula:

$$EPT = \left(GER_{SHC-system} - GER_{Conventional-system}\right) / E_{year}$$

where:

$GER_{SHC\text{-}system}$ is the GER related to the life cycle of the SHC system except for the operation phase;

$GER_{Conventional\text{-}system}$ is the GER related to the life cycle of the conventional system except for the operation phase;

E_{year} is the net yearly primary energy saving due to the use of the SHC system in replacement of a conventional one.

SHC SOLAR HEATING & COOLING PROGRAMME INTERNATIONAL ENERGY AGENCY

KEY PERFORMANCE INDICATOR

Task 53

Key performance indicator name: Energy Return Ratio (ERR)

Typology (economic, energy or environmental, social, technical): Energy indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): -

Description: ERR represents how many times the energy saving overcomes the primary energy consumed during the manufacturing and the end-of-life of the SHC system

Performance target: N.A.

Measurement process: The KPI can be calculated with the formula:

$$ERR = E_{overall} / GER_{SHC-system}$$

where:

$GER_{SHC\text{-}system}$ is the GER related to the life cycle of the SHC system except for the operation phase;

$E_{overall}$ is the net primary energy saving during the overall lifetime of the SHC system due to the use of this system in replacement of a conventional one.

3.1.2 Environmental KPIs

SHC SOLAR HEATING & COOLING PROGRAMME INTERNATIONAL ENERGY AGENCY

KEY PERFORMANCE INDICATOR

Task 53

Key performance indicator name: Global Warming Potential (GWP)

Typology (economic, energy or environmental, social, technical): Environmental indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): kg CO_{2eq}

Description: GWP is a measure of the relative, globally averaged, warming effect arising from the emissions of a particular greenhouse-gas. The GWP represents the time-integrated commitment to climate forcing from the instantaneous release of 1 kg of a trace gas expressed relative to that from 1 kg of carbon dioxide

Performance target: Percentage reduction of GWP during the life cycle of the system (to be fixed case by case)

Measurement process: The KPI can be calculated following a life cycle approach with the formula:

$$GWP = \sum_1^n (m_i * CF_i)$$

where:

m_i is the mass of the substance *i* emitted during the life cycle of the system;

CF_i is the characterization factor that reflects the relative contribution of the substance *i* to the impact on GWP.

KEY PERFORMANCE INDICATOR

Key performance indicator name: Acidification Potential (AP)

Typology (economic, energy or environmental, social, technical): Environmental indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): kg SO_{2eq}

Description: AP measures the impact generated by the emission of airborne acidifying substances (as nitrogen oxides and sulphur dioxide). Acidification refers literally to processes that increase the acidity of water and soil systems by hydrogen ion concentration

Performance target: Percentage reduction of AP during the life cycle of the system (to be fixed case by case)

Measurement process: The KPI can be calculated following a life cycle approach with the formula:

$$AP = \sum_1^n (m_i * CF_i)$$

where:

m_i is the mass of the substance *i* emitted during the life cycle of the system;

CF_i is the characterization factor that reflects the relative contribution of the substance *i* to the impact on AP.

KEY PERFORMANCE INDICATOR

Key performance indicator name: Eutrophication Potential (EP)

Typology (economic, energy or environmental, social, technical): Environmental indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): kg $PO_4^{3-}{}_{eq}$

Description: EP is defined as the potential of nutrients to cause over-fertilization of water and soil which in turn can result in increased growth of biomass. For example, it causes excessive plant growth like algae in rivers which causes severe reductions in water quality and animal populations

Performance target: Percentage reduction of EP during the life cycle of the system (to be fixed case by case)

Measurement process: The KPI can be calculated following a life cycle approach with the formula:

$$EP = \sum_1^n (m_i * CF_i)$$

where:

m_i is the mass of the substance *i* emitted during the life cycle of the system;

CF_i is the characterization factor that reflects the relative contribution of the substance *i* to the impact on EP.

KEY PERFORMANCE INDICATOR

Key performance indicator name: Ozone Depletion Potential (ODP)

Typology (economic, energy or environmental, social, technical): Environmental indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): kg CFC-11_{eq}

Description: ODP indicates the potential for emissions of chlorofluorocarbon compounds and other halogenated hydrocarbons to deplete the ozone layer in the stratosphere, where it shields the earth from harmful ultraviolet radiation

Performance target: Percentage reduction of ODP during the life cycle of the system (to be fixed case by case)

Measurement process: The KPI can be calculated following a life cycle approach with the formula:

$$ODP = \sum_1^n (m_i * CF_i)$$

where:

m_i is the mass of the substance *i* emitted during the life cycle of the system;

CF_i is the characterization factor that reflects the relative contribution of the substance *i* to the impact on ODP.

KEY PERFORMANCE INDICATOR

Key performance indicator name: Photochemical Ozone Creation Potential (POCP)

Typology (economic, energy or environmental, social, technical): Environmental indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): kg C_2H_{4eq}

Description: POCP is related to the potential for volatile organic compounds and oxides of nitrogen to generate photochemical or summer smog in the presence of heat and sunlight

Performance target: Percentage reduction of POCP during the life cycle of the system (to be fixed case by case)

Measurement process: The KPI can be calculated following a life cycle approach with the formula:

$$POCP = \sum_1^n \left(m_i * CF_i \right)$$

where:

m_i is the mass of the substance *i* emitted during the life cycle of the system;

CF_i is the characterization factor that reflects the relative contribution of the substance *i* to the impact on POCP.

KEY PERFORMANCE INDICATOR

Key performance indicator name: GWP Payback Time (GWP-PT)

Typology (economic, energy or environmental, social, technical): Environmental indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): Years

Description: GWP-PT is defined as the time during which the avoided GWP impact due to the use of the SHC system in replacement of a conventional system is equal to GWP impact caused during its manufacturing and end-of-life

Performance target: GWP-PT lower than the useful life of the system

Measurement process: The KPI can be calculated with the formula:

$$GWP - PT = \left(GWP_{SHC-system} - GWP_{Conventional-system} \right) / \, GWP_{year}$$

where:

$GWP_{SHC\text{-}system}$ is the GWP related to the life cycle of the SHC system except for the operation phase;

$GWP_{Conventional\text{-}system}$ is the GWP related to the life cycle of the conventional system except for the operation phase;

GWP_{year} is the net yearly avoided GWP due to the use of the SHC system in replacement of a conventional system.

3.1.3 Economic KPIs

SHC SOLAR HEATING & COOLING PROGRAMME INTERNATIONAL ENERGY AGENCY

KEY PERFORMANCE INDICATOR

Task 53

Key performance indicator name: Money savings during the operation (MSDO)

Typology (economic, energy or environmental, social, technical): Economic indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): €

Description: MSDO represents the money saving during the useful life of the SHC system due to its lower energy (electricity and natural gas) consumption if compared with a conventional system

Performance target: N.A.

Measurement process: The KPI can be calculated with the formula:

$$MSDO = \sum_{1}^{n} \begin{pmatrix} \left(NG_{Conventional-system-i} - NG_{SHC-system-i} \right) * NG_{price-i} + \\ + \left(EL_{Conventional-system-i} - EL_{SHC-system-i} \right) * EL_{price-i} \end{pmatrix}$$

where:

$NG_{Conventional\text{-}system\text{-}i}$ is the natural gas consumption of the conventional system in the year *i*, expressed in MJ or in kWh;

$NG_{SHC\text{-}system\text{-}i}$ is the natural gas consumption of the SHC system in the year *i*, expressed in MJ or in kWh;

$NG_{price\text{-}i}$ is the price of natural gas in the year *i*, expressed in €/MJ or in €/kWh;

$EL_{Conventional\text{-}system\text{-}i}$ is the electricity consumption of the conventional system in the year *i*, expressed in MJ or in kWh;

$EL_{SHC\text{-}system\text{-}i}$ is the electricity consumption of the SHC system in the year *i*, expressed in MJ or in kWh;

$EL_{price\text{-}i}$ is the price of electricity in the year *i*, expressed in €/MJ or in €/kWh.

KEY PERFORMANCE INDICATOR

Key performance indicator name: Initial cost ratio (ICR)

Typology (economic, energy or environmental, social, technical): Economic indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): -

Description: ICR is the ratio between the price set by supplier/vendor in their price list when the customer purchases the SHC system and the corresponding price of the conventional system

Performance target: Lower than 1

Measurement process: The KPI can be calculated with the formula:

$$ICR = P_{SHC-system} \, / \, P_{Conventional-system}$$

where:

$P_{SHC\text{-}system}$ is the price of the SHC system defined by the supplier/vendor;
$P_{Conventional\text{-}system}$ is the price of the conventional system defined by the supplier/vendor.

Both $P_{SHC\text{-}system}$ and $P_{Conventional\text{-}system}$ can be found by the customer in the price list given by the supplier/vendor.

KEY PERFORMANCE INDICATOR

Key performance indicator name: Operation/maintenance costs ratio (OMC)

Typology (economic, energy or environmental, social, technical): Economic indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): -

Description: OMC is the ratio between the cost to the customer during the useful life of the SHC system for its operation and maintenance (regular maintenance and repair) and the corresponding cost of the conventional system

Performance target: Lower than 1

Measurement process: The KPI can be calculated with the formula:

$$OMC = \frac{\left(NG_{SHC-system-i} * NG_{price-i} + EL_{SHC-system-i} * EL_{price-i} + M_{Cost-SHC-system-i}\right)}{\left(NG_{Conv.-system-i} * NG_{price-i} + EL_{Conv.-system-i} * EL_{price-i} + M_{Cost-Conv.-system-i}\right)}$$

$NG_{SHC\text{-}system\text{-}i}$ is the natural gas consumption of the SHC system in the year *i*, expressed in MJ or in kWh;
$NG_{Conv.\text{-}system\text{-}i}$ is the natural gas consumption of the conventional system in the year *i*, expressed in MJ or in kWh;
$NG_{price\text{-}i}$ is the price of natural gas in the year *i*, expressed in €/MJ or in €/kWh;
$EL_{SHC\text{-}system\text{-}i}$ is the electricity consumption of the SHC system in the year *i*, expressed in MJ or in kWh;
$EL_{Conv.\text{-}system\text{-}i}$ is the electricity consumption of the conventional system in the year *i*, expressed in MJ or in kWh;
$EL_{price\text{-}i}$ is the price of electricity in the year *i*, expressed in €/MJ or in €/kWh;
$M_{Cost\text{-}SHC\text{-}system\text{-}i}$ is the cost for the maintenance of the SHC system in the year *i*;

$M_{Cost\text{-}Conv.\text{-}system\text{-}i}$ is the cost for the maintenance of the conventional system in the year *i*.

KEY PERFORMANCE INDICATOR

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY
Task 53

Key performance indicator name: Payback period (PP)

Typology (economic, energy or environmental, social, technical): Economic indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): Years

Description: PP is the time in which the initial cash outflow of an investment for the SHC system is expected to be recovered from the economic benefit (positive cash flow) generated by the investment

Performance target: PP lower than the useful life of the system

Measurement process: The formula to calculate the KPI depends on whether the economic benefit (positive cash flow) per period is even or uneven.

In case it is even, the formula to calculate the KPI period is:

$$PP = P_{SHC-system} / B_{annual}$$

Where:

$P_{SHC\text{-}system}$ is the price of the SHC system defined by the supplier/vendor;

B_{annual} is the net annual benefit (positive cash flow) due to the use of the SHC system in replacement of a conventional one in terms of decrement in expenditure for electricity and natural gas.

When the economic benefit is uneven, it is needed to calculate the cumulative net cash flow for each period and then use the following formula for the KPI:

$$PP = A + B/C$$

Where:

A is the last period with a negative cumulative cash flow;

B is the absolute value of cumulative cash flow at the end of the period A;

C is the total cash flow during the period after A.

3.1.4 Social KPI

KEY PERFORMANCE INDICATOR

Key performance indicator name: Customer satisfaction (CS)

Typology (economic, energy or environmental, social, technical): Social indicator

Type of assessment (qualitative or quantitative): Qualitative

Unit of measure (only for quantitative KPI): N.A.

Description: CS indicates how satisfied the client is with the SHC system

Performance target: Positive value of CS

Measurement process: The KPI can be estimated by using the following qualitative judgments:

- Totally satisfied (positive value);
- Mostly satisfied (positive value);
- Neither satisfied nor dissatisfied(neither positive nor negative value);
- Mostly dissatisfied (negative value);
- Totally dissatisfied (negative value).

KEY PERFORMANCE INDICATOR

Key performance indicator name: Ease of use of the system (EUS)

Typology (economic, energy or environmental, social, technical): Social indicator

Type of assessment (qualitative or quantitative): Qualitative

Unit of measure (only for quantitative KPI): N.A.

Description: EUS indicates the ease of use of the SHC system

Performance target: Positive value of EUS

Measurement process: The KPI can be estimated by using the following qualitative judgments:

- Very easy to use (positive value);
- Easy enough to use (positive value);
- Neither easy nor difficult to use (neither positive nor negative value);
- Not very easy to use (negative value);
- Not easy to use (negative value).

3.1.5 Technical KPI

KEY PERFORMANCE INDICATOR

Key performance indicator name: Useful life of the system (ULS)

Typology (economic, energy or environmental, social, technical): Technical indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): Year

Description: ULS indicates the period during which the system is expected to be usable for the purpose it was acquired

Performance target: N.A.

Measurement process: The KPI can be estimated based on the indications given by the supplier/vendor.

KEY PERFORMANCE INDICATOR

Key performance indicator name: Thermal Performance Coefficient (COP_{th}) of the ab/adsorption machine

Typology (economic, energy or environmental, social, technical): Technical indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): -

Description: COP_{th} is the ratio between the thermal cooling energy supplied by the evaporator and the thermal heat energy supplied to the generator of the sorption machine

Performance target: To be fixed case by case

Measurement process: The KPI can be calculated with the formula:

$$COP_{th} = Q_{Cool-Ev} / Q_{Heat-generator}$$

where:

$Q_{Cool-Ev}$ is the thermal cooling energy supplied by the evaporator;

$Q_{Heat-generator}$ is the thermal heat energy supplied to the generator of the sorption machine.

KEY PERFORMANCE INDICATOR

Key performance indicator name: Solar Electric Performance Coefficient ($COP_{Elec-sol}$) of the system

Typology (economic, energy or environmental, social, technical): Technical indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): -

Description: $COP_{Elec-sol}$ corresponds to the ratio of the system's useful solar energy to auxiliary consumption

Performance target: To be fixed case by case

Measurement process: The KPI can be calculated with the formula:

$$COP_{Elec-sol} = ESU / E_{Aux-sol}$$

where:
ESU refers to the thermal solar energy exploited by the system integrating thermal losses from hot and cold storage;
$E_{Aux-sol}$ Electricity consumption of the solar system auxiliaries.

KEY PERFORMANCE INDICATOR

Key performance indicator name: Reliability of the system (RS)

Typology (economic, energy or environmental, social, technical): Technical indicator

Type of assessment (qualitative or quantitative): Quantitative

Unit of measure (only for quantitative KPI): %

Description: RS at time *t* is the probability that the system will perform its function without failure under stated conditions in the interval [0, *t*)

Performance target: RS higher than 90%

Measurement process: The KPI can be calculated with the formula:

$$RS(t) = P(X > t)$$

where:
X is a random variable that represents the time to occurrence of system failure.

3.2 Definition of a quality labeling scheme for solar cooling systems

The quality label scheme for market available and new generation solar cooling systems is a scheme including the following characteristics of the investigated system:

- Picture of the system;
- Brief description of the system;
- Energy KPIs;
- Environmental KPIs;
- Economic KPIs;
- Social KPIs;
- Technical KPIs.

QUALITY LABEL SCHEME

Task 53

(Insert a picture of the system)	**The system** (insert a brief description of the system)

Energy KPIs GER (MJ): EPT (years): ERR:	**Environmental KPIs** GWP (kg CO_{2eq}): AP (kg SO_{2eq}): EP (kg $PO_4^{3-}{}_{eq}$): ODP (kg CFC-11_{eq}): POCP (kg C_2H_{4eq}): GWP-PT (year):
Economic KPIs MSDO (€): ICR (€): OMC (€): PP (years):	**Social KPIs** CS: EUS:

Technical KPIs

ULS (years):

COP_{th}:

$COP_{Elec\text{-}sol}$:

RS (%):

Key of KPIs

Energy indicators: Global Energy Requirement (GER); Energy Payback Time (EPT); Energy Return Ratio (ERR);

Environmental indicators: Global Warming Potential (GWP); Acidification Potential (AP); Eutrophication Potential (EP); Ozone Depletion Potential (ODP); Photochemical Ozone Creation Potential (POCP); GWP Payback Time (GWP-PT);

Economic indicators: Money savings during the operation (MSDO); Initial cost ratio (ICR); Operation/maintenance costs ratio (OMC); Payback period (PP);

Social indicators: Customer satisfaction (CS); Ease of use of the system (EUS);

Technical indicators: Useful life of the system (ULS); Thermal performance coefficient of the ab/adsorption machine (COP_{th}); Solar Electric Performance Coefficient of the system ($COP_{Elec-sol}$); Reliability of the system (RS).

4. Conclusions

This technical report described the research activities developed within Subtasks A: “Components, Systems & Quality, Activity A5 “LCA and techno-eco comparison between reference and new systems”.
Subtask A – Activity A5-1 was organized in two steps: the first step regarding the analysis of 13 literature studies on environmental and, in some cases, economic analysis of solar heating and cooling systems; the second step regarding the development of a LCA and, where possible, a the techno-economic analysis, of 5 systems examined within Subtask A.
Subtask A – Activity A5-2 focused on the selection of key performance indicators for describing the main characteristics (technical, economic, energy, environmental, social) of solar heating and cooling systems. In detail, were selected 3 energy KPIs, e environmental KPIs, 4 economic KPIs, 2 social KPIs and 4 technical KPIs. In addition a quality-labeling scheme was created for reporting a clear and synthetic description of the main characteristics/impacts (technical, economic, energy, environmental, social) of the systems.

Activity A5 also included the development of ELISA “**E**nvironmental **L**ife-cycle **I**mpacts of **S**olar **A**ir-conditioning systems”, a simplified tool for assessing the life cycle energy and environmental impacts/benefits due to the use of solar heating and cooling systems in substitution of conventional ones, and to support the introduction of life cycle considerations in the selection of the most environmentally sustainable heating and cooling system is a specific geographic contexts.

5. Bibliography

Beccali, M., Cellura, M., Longo, S., Nocke, B., & Finocchiaro, P., 2012. LCA of a solar heating and cooling system equipped with a small water-ammonia absorption chiller. Solar Energy, 86(5), 1491-1503.

Beccali, M., Cellura, M., Finocchiaro, P., Guarino, F., Longo, S., Nocke, B., 2014. Life Cycle performance assessment of small solar thermal cooling systems and conventional plants assisted with photovoltaics. Solar Energy, Volume 104, 93-102.

Beccali, M., Cellura, M., Longo, S., Guarino, F., 2016. Solar heating and cooling systems versus conventional systems assisted by photovoltaic: Application of a simplified LCA tool. Sol. Energy Mater. Sol. Cells 156, 92–100.

Bukoski, J., Gheewala, S. H., Mui, A., Smead, M., & Chirarattananon, S., 2014. The life cycle assessment of a solar-assisted absorption chilling system in Gangkok, Thailand. Energy and Buildings, 72, 150-156.

BUWAL250, 1998. Bundesamt für Umwelt, Wald und Landschaft, Ökoinventar für Energie systeme, Berne, Switzerland.

European Commission, Joint Research Centre, 2012. Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods: database and supporting information, European Commission.

E.U.ESU Group, 1996. ETH-ESU96 Okoinventare von Energie systemen.

Finocchiaro, P., Beccali, M., Cellura, M., Guarino, F., Longo, S., 2016. Life cycle assessment of a compact desiccant evaporative cooling system: the case study of the "Freescoo”. Solar Energy Materials and Solar Cells 156, 83-91.

Florides, G.A., Kalogirou, S.A., Tassou, S.A., Wrobel, L.C., 2002. Modelling, simulation and warming impact assessment of a domestic-size absorption solar cooling system, Applied Thermal Engineering, 22: 1313-1325.

Frischknecht, R., Jungbluth, N., Althaus, H.J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., 2005. The ecoinvent database: Overview and methodological framework. Int. J. Life Cycle Assess. 10, 3–9. doi:10.1065/lca2004.10.181.1

Frischknecht, R., Editors, N.J., Althaus, H., Bauer, C., Doka, G., Dones, R., Hischier, R., Hellweg, S., Köllner, T., Loerincik, Y., Margni, M., 2007. Implementation of Life Cycle Impact Assessment Methods. Am. Midl. Nat. 150, 1–151.

Gebreslassie, B. H., Guillén-Gosálbez, G., Jiménez, L., & Boer, D., 2009. Design of environmentally friendly absorption cooling systems via multi-objective optimization and life cycle assessment. Applied Energy 86, 1712-1722.

Gebreslassie, B. H., Guillén-Gosálbez, G., Jiménez, L., Boer, D. 2010. A systematic tool for the minimization of the life cycle impact of solar assisted absorption cooling systems, Energy 35, 3849-3862.

Hang, Y., Qu, M., Zhao, F., 2011. Economical and environmental assessment of an optimized solar cooling system for a medium-sized benchmark office building in Los Angeles, California, Renewable Energy, 36: 648-658.

Hang, Y., Qu, M., Winston, R., Jiang, L., Widyolar, B., Poiry, H., 2014. Experimental based energy performance analysis and life cycle assessment for solar absorption cooling system at University of Californian, Merced. Energy Build. 82, 746–757.

ISO, 2006a. ISO 14040: Environmental management — Life Cycle Assessment — Principles and Framework, International Organization for Standardization.

ISO, 2006b. ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines, International Organization for Standardization.

Jing, Y.Y., Bai, H., Wang, J.J, Liu, L., 2012. Life cycle assessment of a solar combined cooling heating and power system in different operation strategies, Applied Energy, 92: 843-853.

Joint Research Center, 2016. EPLCA – European Reference Life-Cycle Database. ⟨http://eplca.jrc.ec.europa.eu/ELCD3/index.xhtml⟩.

Kalogirou, S., 2009. Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters. Sol. Energy 83, 39–48. doi:10.1016/j.solener.2008.06.005

Longo, S., Palomba, V., Beccali, M., Cellura, M., Vasta, S., 2017. Energy balance and life cycle assessment of small size residential solar heating and cooling systems equipped with adsorption chillers. Solar Energy 158, 543-558.

Marcos, J.D., Izquierdo, M., Parra, D., 2011. Solar space heating and cooling for Spanish housing: potential energy savings and emissions reduction. Sol. Energy 85, 2622–2641.

Martinopoulos, G., Tsilingiridis, G., Kyriakis, N., 2013. Identification of the environmental impact from the use of different materials in domestic solar hot water systems. Appl. Energy 102, 545–555.

Martinopoulos, G., Tsilingiridis, G., 2014. Active solar heating systems for energy efficient buildings in Greece: a technical economic and environmental evaluation. Energy Build. 68, 130–137.

Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., 2013. IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC.