Life Cycle Assessment experiences for solar heating and cooling systems

Marco Beccali[1], Maurizio Cellura[1], Maria Anna Cusenza[1], Sonia Longo[1], Daniel Mugnier[2], Tim Selke[3] and Vicente Quiles Pedro Gines[4]

[1] University of Palermo - Department of Energy, Information Engineering and Mathematical Models (DEIM), Palermo (Italy)

[2] TECSOL, Perpignan (France)

[3] AIT Austrian Institute of Technology GmbH, Vienna (Austria)

[4] Universidad Miguel Hernandez, Elche (Spain)

Abstract

Solar heating and cooling systems can significantly contribute to the energy and climate European goals. A complete assessment of this contribution needs the analysis of these systems from a life-cycle perspective, in order to estimate the energy and environmental costs of their manufacturing and end-of-life, and to compare these costs with the benefits obtained during operation. A well-established methodology to fulfil this task is the Life Cycle Assessment (LCA). The paper describes some LCA experiences of solar heating and cooling systems, developed within the Task 53 "New generation solar cooling & heating systems (PV or solar thermally driven systems)" of the International Energy Agency. The results of these analyses can be useful to orientate manufacturers, researchers and decision makers for a more sustainable use of solar technologies.

Keywords: solar heating and cooling, life cycle assessment, sustainability, environmental impacts

1. Introduction

Solar heating and cooling (SHC) systems can significantly contribute to the energy and climate European goals (European Commission, 2014; European Commission, 2011) by reducing the use of fossil fuels and the related environmental impacts for building air-conditioning (Beccali et al., 2016; Bukoski et al., 2014; Longo et al., 2017).

The SHC systems mainly use energy from renewable sources during operation. However, they consume energy and cause environmental impacts during the whole life cycle (manufacturing, operation and end-of-life) (Beccali et al., 2014). Thus, to correctly assess the real benefits due to the installation of SHC technologies, their life cycle energy and environmental impacts should be estimated (Beccali et al., 2012a; Finocchiaro et al., 2016).

A useful tool to assess resource use, energy and environmental burdens related to the full life cycle of products and services is the Life Cycle Assessment (LCA) methodology (ISO, 2006a, 2006b).

In this paper, some experiences of LCA applied to SHC systems are described, developed within the Task 53 "New generation solar cooling & heating systems (PV or solar thermally driven systems)" of the International Energy Agency (IEA) (Mugnier et al., 2015).

2. Description of the examined systems

The SHC systems examined in this study are the following:

- a PV – air conditioner unit (S1);
- a PV cooling system based on an air to water compression chiller (working fluid: propane) (S2);
- a compact desiccant evaporative cooling system, called "Freescoo" (S3).

The system S1 is designed to operate by using the electricity produced by a photovoltaic plant. The main components of the PV – air conditioner system are the PV panels and the air conditioning unit (Fig. 1).

doi:10.18086/eurosun2018.04.13 Available at http://proceedings.ises.org

a) PV - Air conditioner: external unit

b) PV - Air conditioner: internal unit

Fig. 1: PV – air conditioner system

The system S2 is a PV cooling designed to operate by using the electricity produced by a photovoltaic power plant. The main components of S2 are the PV system, the heat pump and the chilled water circuit (Fig. 2).

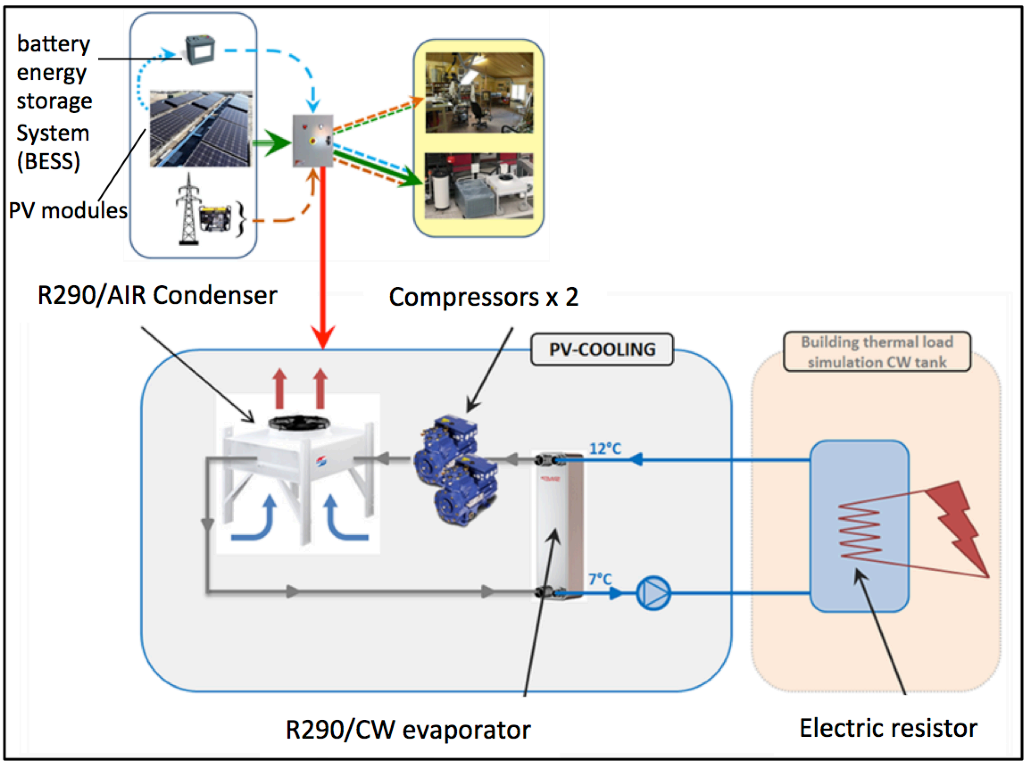

Fig. 2: PV – cooling system scheme

The system S3 (Fig. 3) is designed for air-conditioning in buildings and it is composed by a solar photovoltaic/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.

Fig. 3: Compact desiccant evaporative cooling system

3. Life Cycle Assessment of the three systems

The LCA is a standardized methodology widely adopted by the scientific community to assess the environmental impacts of products and services from a life cycle perspective (i.e. including extraction of raw materials, transports, manufacturing process, use and end-of-life) (ISO, 2006a, 2006b).

The LCA consists of four steps, briefly described in the following:

- Goal and scope definition. In this step the intended application(s) and the object of the study (i.e. the exact product or other system(s) to be analysed) are described and defined in detail (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). This step also includes the identification of system boundaries (unit processes that are part of a product system), functional unit (quantified performance of a product system for use as a reference unit), allocation procedures, selected impact categories and impact assessment methodologies, etc.
- Life Cycle Inventory (LCI) analysis. This step involves data collection and calculation procedures to quantify the resources consumption, the air, water and soil emissions, and the waste production.
- Life Cycle Impact Assessment (LCIA). This step is aimed at evaluating the significance of potential environmental impacts using the LCI result.
- Life cycle interpretation. In the final step of the LCA the results of a LCI and/or a LCIA are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.

The LCA methodology allows to capture the complexity hidden behind a product/service and to identify opportunities to improve its environmental performance at various phases of the life cycle preventing the risk to shift the impacts from one life cycle phase to another (i.e. from use phase to manufacturing one) and/or from one impact category to another.

3.1 Goal and scope definition

The goal of the study was to assess the energy and the environmental impacts caused by three different SHC systems and to highlight the potentials of the LCA methodology in evaluating the performance of this kind of systems in terms of impacts associated to a wide range of environmental categories.

The selected functional units (FUs) are:

- For the S1 system, the PV – air conditioner (FU_1);
- For the S2 system, the PV cooling (FU_2);
- For the S3 system, the FU is represented by a system with a useful life of 15 years that provides cooling and heating for the building, considering a cooling solar fraction of about 0.85 (FU_3).

The system boundaries include the manufacturing step for the S1 and S2 systems, while the whole life cycle was investigated for the last one, 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).

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 potential (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 characterization 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 and Joint Research Centre, 2012).

The eco-profiles of materials and energy sources used to produce the main components of the analysed FUs are based on the Ecoinvent database (Frischknecht et al., 2005; Wernet et al., 2016) Impacts of end-of-life, only for FU_3, 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).

3.2 Life Cycle Inventory

This step was finalized to the first hand data collection (primary data) concerning the main inputs and outputs in terms of materials, components, energy sources and waste production. In addition, specific energy and environmental impacts (secondary data) of the above inputs and outputs were identified by using environmental databases (Wernet et al., 2016).

In the following, the authors describe the data collection related to each investigated SHC system.

Data collection – S1 system

The data 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).

Data collection – S2 system

The data are referred to the data sheet provided by the manufacturer. The PV system consists in 18 monocrystalline photovoltaic modules and in a battery energy storage system (BESS). The modules are connected in parallel. The nominal power of each panel is 280 Wp. The overall nominal capacity is 5.04 kWp. 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 compressors. 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);
- 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.

The chilled water circuit 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 (which was not considered in the inventory). 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).

Data collection – S3 system

Data were 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 equipments:

- 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 electrovalves;
- 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.

In the operation phase (Tab.1-2) 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. 2,590 l of water have been considered as well. A useful life of 15 years is expected for the system.

Tab. 1: Cooling season, use phase data for system S3

Consumption	Unit of measure	Value
Cooling energy delivered to the building	kWh/day	13.32
Electricity consumed (cooling mode)	kWh/day	1.04
Electricity from the grid (cooling mode)	kWh/day	0.26
Water consumption	l/day	28.78

Tab. 2: Heating season, use phase data for system S3

Consumption	Unit of measure	Value
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

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.

3.3 Life Cycle Impact Assessment: results and interpretation

In the following, the impacts on GER of each examined SHC system are indicated.

Concerning the S1 system, the GER of the PV – air conditioner manufacturing is 2.60E+04 $MJ_{primary}$ of which 86% is non – renewable primary energy. The PV panels manufacturing is responsible for the highest primary energy consumption. In detail, this component causes 88% of the GER (Fig. 4).

The GER of manufacturing phase of the PV – cooling unit (S2) is 2.86E+05 $MJ_{primary}$ of which 88% is non – renewable primary energy. The PV panels manufacturing and the chilled water circuit are responsible for the highest primary energy consumptions (Fig. 5). In detail, they account, respectively, for 71% and 16% of the GER.

The impact on GER of the system S3 is 3.59E+04 $MJ_{primary}$, of which 75.7% is caused during the construction phase, 11.2% during operation and the remaining 13.1% during the end-of-life (Fig. 6).

The environmental impacts associated to the examined SHC systems are shown in Tab. 3.

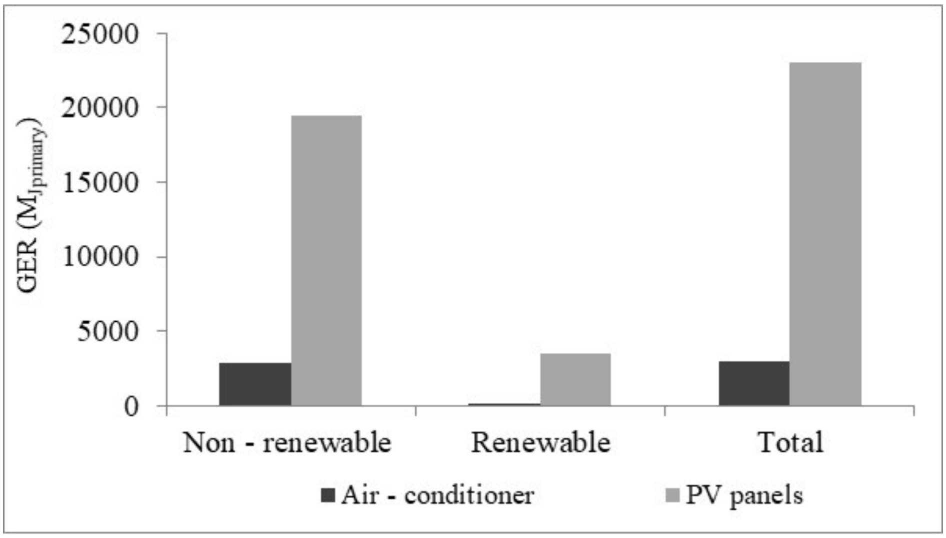

Fig. 4: GER processes contribution of the manufacturing phase – S1

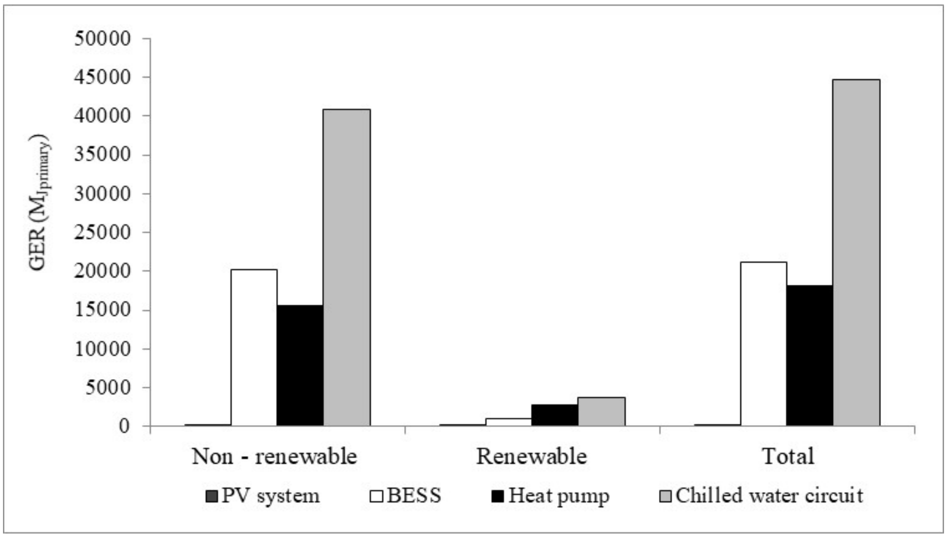

Fig. 5: GER processes contribution of the manufacturing phase – S2

Fig. 6: GER processes contribution of each life cycle phase – S3

Tab. 3: Environmental impacts of the examined SHC systems

Impact category	**S1**	**S2**	**S3**
GWP (kg CO_{2eq})	1.87E+03	4.57E+03	2.15E+03
ODP (kg CFC-11_{eq})	1.21E-02	1.28E-02	2.19E-04
HT-ce (CTUh)	2.66E-04	8.85E-03	7.10E-04
HT-nce (CTUh)	2.26E-03	2.22E-03	2.36E-03
PM (kg PM2.5_{eq})	7.63E-01	5.43E+00	5.32E+02
IR-hh (kBq $U^{235}{}_{eq}$)	3.96E+02	4.91E+02	4.12E+02
IR-e (CTUe)	1.21E-03	1.59E-03	1.25E-03
POFP (kg $NMVOC_{eq}$)	5.13E+00	1.71E+01	6.84E+00
AP (molc $H^{+}{}_{eq}$)	8.90E+00	3.74E+01	1.45E+01
T-EU (molc N_{eq})	1.43E+01	5.50E+01	2.22E+01
F-EU (kg P_{eq})	1.50E+00	5.76E+00	1.63E+00
M-EU (kg N_{eq})	1.50E+00	6.25E+00	2.13E+00
F-E (CTUe)	5.32E+04	2.30E+05	5.64E+04
LU (kg $C_{deficit}$)	1.20E+03	9.07E+03	2.05E+03
WRD ($m^3 water_{eq}$)	4.80E+03	8.87E+00	4.86E+03
MFRRD ($kgSb_{eq}$)	6.35E-01	5.87E+00	3.13E-01

Fig. 7 shows the process contribution of the manufacturing phase of S1 on the examined impact categories. 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.

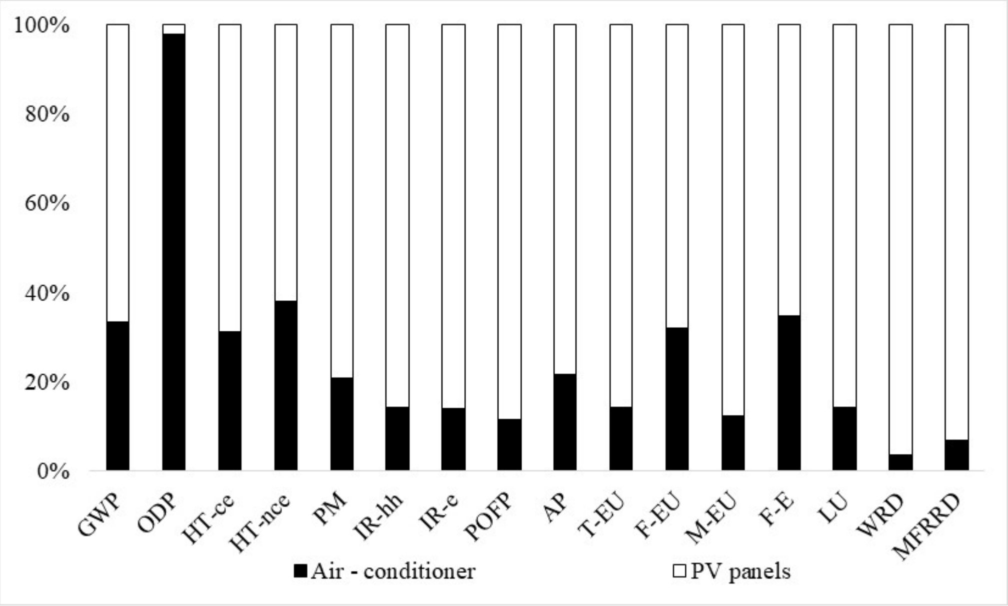

Fig. 7: Environmental impacts processes contribution – S1

Fig. 8 illustrates the contribution of each component of the S2 system to the examined impact categories. The PV panels account for the highest impact in all the examined impact categories. The only exceptions are the ODP and MFRRD, for which they represent about 12% and 40% of the overall impact, respectively. The contribution of the PV in the other impact categories ranges 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 gives an impact variable from 0.8% for ODP to 35.6% for HT-nce.

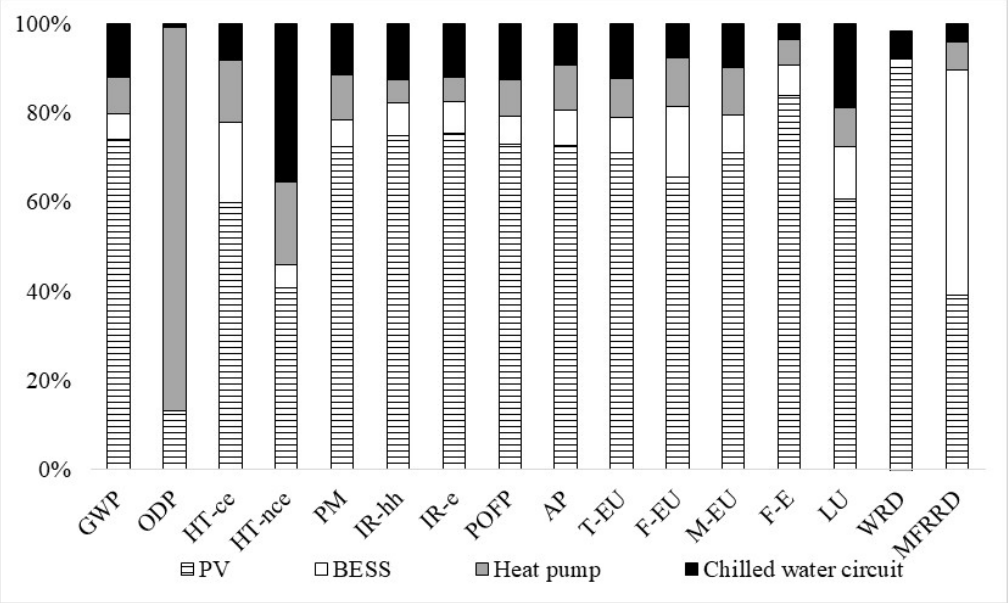

Fig. 8: Environmental impacts processes contribution – S2

With reference to the S3 system, Fig. 9 illustrates the share of each life cycle impact on the total impacts.

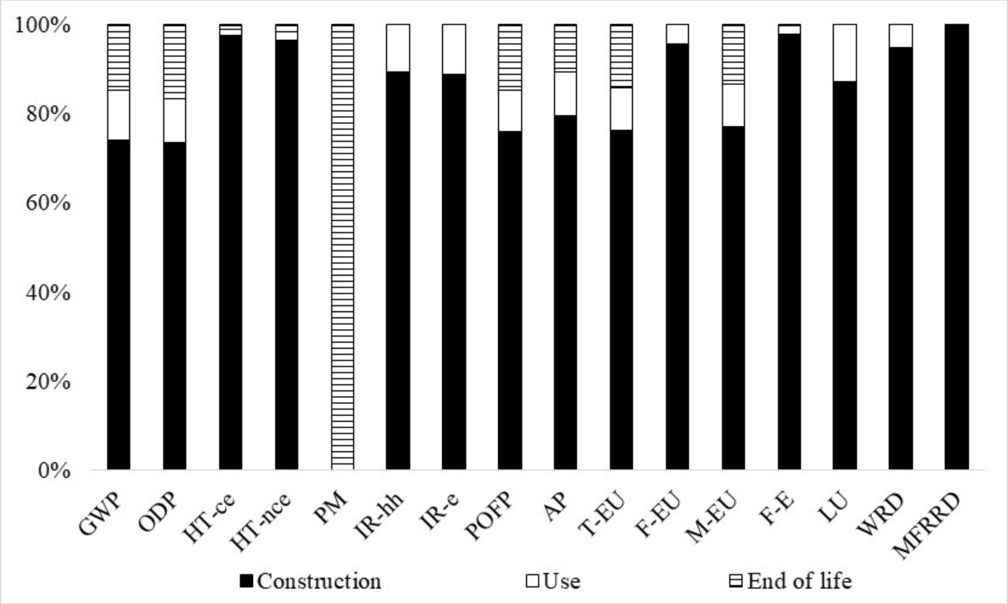

Fig. 9: Environmental impacts share of each life cycle phase – S3

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%.

A detailed analysis of the manufacturing phase was carried out and the main outcomes are briefly discussed in the following bullet points:

- the highest share of impacts in DEC based processes is associated to the adsorbent beds, 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%;
- in systems using PV collectors:
    - the external frames impacts are variable between the 3.18% of HT-nce to the 10.34% of HT-ce;
    - the internal frames result 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.

4. Conclusions

The results of the LCA analyses allowed identifying the main energy and environmental “hot spots” to be taken into account for improving the environmental sustainability of the SHC systems. In detail, the results showed that the PV panels account for the highest impact caused during the manufacturing of the PV cooling system and the PV – air conditioner unit. The only exception is for ODP mainly caused by the heat pump (about 86%) in the first system and by the air conditioner (about 98%) in the second one. Referring to the compact desiccant evaporative cooling system (S3), the manufacturing step has a predominant weight in most of the impact categories, reaching values above or close 95% in the case of the freshwater ecotoxicity, freshwater eutrophication and human toxicity.

The most impacting components to the above impact categories are the solar batteries (about 40%).

The results of the research can represent a “knowledge basis” to assess the real advantages arising from the installation of SHC technologies for reducing the energy and environmental impacts of buildings air-conditioning and to orientate manufacturers, researchers and decision makers for a more sustainable use of solar technologies.

5. References

Beccali, M., Cellura, M., Longo, S., Nocke, B., Finocchiaro, P., 2012a. LCA of a solar heating and cooling system equipped with a small water-ammonia absorption chiller. Sol. Energy 86, 1491–1503. https://doi.org/10.1016/j.solener.2012.02.010Beccali, M., Cellura, M., Longo, S., Nocke, B., Finocchiaro, P., 2012a. LCA of a solar heating and cooling system equipped with a small water-ammonia absorption chiller. Sol. Energy 86, 1491–1503. https://doi.org/10.1016/j.solener.2012.02.010

Beccali, M., Finocchiaro, P., Nocke, B., 2012b. Energy performance evaluation of a demo solar desiccant cooling system with heat recovery for the regeneration of the adsorption material. Renew. Energy 44, 40-52. https://doi.org/10.1016/j.renene.2011.12.021

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. Sol. Energy 104, 93-102, https://doi.org/10.1016/j.solener.2013.10.016

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. https://doi.org/10.1016/j.solmat.2016.03.025

Bukoski, J., Gheewala, S.H., Mui, A., Smead, M., Chirarattananon, S., 2014. The life cycle assessment of a solar-assisted absorption chilling system in Bangkok, Thailand. Energy Build. 72, 150-156. https://doi.org/10.1016/j.enbuild.2013.12.034

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

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

European Commision, 2014. A policy framework for climate and energy in the period from 2020 to 2030. https://Ec.Europa.Eu/Energy/En/Topics/Energy-Strategy/2030-Energy-Strategy Brussels.

European Commission, 2011. COMMUNICATION FROM THE COMMISION: A Roadmap for moving to a competitive low carbon economy in 2050. COM(2011) 112 Final 34, 1–34.

European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union; 2010.

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

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.” Sol. Energy Mater. Sol. Cells 156, 83–91. https://doi.org/10.1016/j.solmat.2016.03.026

Frischknecht, R., Jungbluth, N., 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.

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.

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.

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. https://doi.org/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. Sol. Energy 158, 543-558. https://doi.org/10.1016/j.solener.2017.10.009

Mugnier, D., Fedrizzi, R., Thygesen, R., Selke, T., 2015. New Generation Solar Cooling and Heating Systems with IEA SHC Task 53: Overview and First Results. Energy Procedia 70, 470-473. https://doi.org/10.1016/j.egypro.2015.02.149

Samuel, D.G.L., Nagendra, S.M.S., Maiya, M.P., 2013. Passive alternatives to mechanical air conditioning of building: Areview. Build. Environ. 66, 54-64. https://doi.org/10.1016/j.buildenv.2013.04.016

Santamouris, M., Kolokotsa, D., 2013. Passive cooling dissipation techniques for buildings and other structures: The state of the art. Energy Build. 57, 74-94. https://doi.org/10.1016/j.enbuild.2012.11.002

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8