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A simplified LCA tool for solar heating and cooling systems

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Abstract

This paper presents a user-friendly Life Cycle Assessment tool, which aims to support researchers, designers and decision-makers in evaluating the life cycle energy and environmental advantages related to the use of solar heating and cooling (SHC) systems in substitution of conventional ones, considering specific climatic conditions and building loads.
The tool was developed within the Task 48 "Quality Assurance & Support Measures for Solar Cooling Systems", promoted by the International Energy Agency in the framework of the SHC Programme.

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Keywords: SHC systems; LCA; energy and environmental performances; payback time indices.

1. Introduction

Good energy performance of SHC systems during the operation step can be generally achieved through an accurate design, which takes into account climate characteristics and building loads [1, 2]. However, by extending the analysis to the systems life cycle, additional "hidden" elements that affect the global performance of a given equipment must be introduced [3].

A well-established methodology for assessing the energy and environmental performances associated with all stages of a system's life cycle is the Life Cycle Assessment (LCA) regulated by the international standards of ISO

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14040 series [4, 5]. The life cycle thinking approach allows taking into account the resources use and environmental burdens related to the full life cycle of the examined systems.

The development of a complete LCA (including manufacturing, operation and end-of-life) for complex systems such as the SHC technologies can be a time and human resources intensive exercise.

For this reason, to have simplified and quick calculation tools for assessing the energy and environmental performances of SHC systems during their life cycle seems useful to support researchers, designer and decision-maker to understand the real benefits of this technology in substitution of conventional ones.

Nomenclature

EPT	Energy Payback Time
ERR	Energy Return Ratio
GER	Global Energy Requirement
GWP	Global Warming Potential
GWP-PT	Global Warming Potential Payback Time
LCA	Life Cycle Assessment
SHC	Solar Heating and Cooling

2. The LCA tool for solar heating and cooling systems

A user-friendly LCA tool has been developed for calculating life cycle energy and environmental balances of SHC systems localized in different geographic contexts. It is able to carry out simplified LCAs and to compare SHC systems with conventional technologies [6].

The use of the tool enables users to calculate the following indices, both for SHCs and for conventional systems:

- Global energy requirement (GER), which represents the total primary energy consumption during the life cycle of a product or a service. The index is expressed in terms of MJ and is calculated by using the Cumulative Energy Demand method [7];
- Global warming potential (GWP), expressed as kg of CO_2 equivalent, which measures the warming effect arising from the emissions of greenhouse gases. GWP is calculated by applying the IPCC 2013 method [8];
- Energy payback time (EPT), which indicates the time during which the SHC system must work to harvest as much primary energy as it requires for its manufacturing and end-of-life. The harvested energy is considered as net of the energy expenditure for the system use. EPT can be calculated as the ratio of a) the difference between the primary energy consumed by the SHC system during the manufacturing and end-of-life steps and the corresponding primary energy for the conventional system and b) the net yearly primary energy saving due to the use of the SHC system instead of the conventional system;
- GWP payback time (GWP-PT), defined as the time during which the avoided GWP impact due to the use of the SHC system is equal to GWP impact caused during its manufacturing and end-of-life. It is the ratio of a) the difference between the GWP generated by the SHC system during the manufacturing and end-of-life steps and the corresponding GWP generated by the conventional system and b) the net yearly avoided GWP due to the use of the SHC system in place of the conventional one;
- Energy return ratio (ERR), which represents how many times the energy saving overcomes the global energy consumption due to the SHC system. ERR is defined as the ratio of the net primary energy saving due to the use of the SHC system during its overall lifetime and the primary energy consumed by the SHC system during the manufacturing and end-of-life steps.

The tool has been developed as an Excel spreadsheet (xls) and it is provided with a user guide. It can be used both by LCA practitioners and by non-professional users for teaching and non-commercial research activities only. Users can build up a LCA model by using a clear and transparent structure, constituted by the worksheets listed in Table 1.

Table 1. Structure of the LCA tool.

Worksheet number	Description
1	SHC system
2	Conventional system
3	Specific impacts SHC system
4	Specific impacts conventional system
5	Total impacts SHC system
6	Total impacts conventional system
7	Impacts comparison
8	Payback indices

2.1. Description of the tool: a demonstration case study

This chapter describes an example of application of such tool to a Solar Heating and Cooling system installed in Palermo (south of Italy) and working with a cold backup configuration (in summer operations an auxiliary conventional chiller supports the absorption chiller). The system has a useful life of 25 years, and is composed by: an absorption chiller (12 kW); a field of evacuated solar collectors (35 m^2); a heat storage (2000 l); a cooling tower (32 kW); an auxiliary gas boiler (10 kW); an auxiliary conventional chiller (10 kW); pipes (60 m); two pumps (80 W and 250 W). The system uses a water/ammonia solution (15 kg of ammonia and 10 kg of water) and, during the operation, it consumes 1,117 kWh/year of electricity and 414/year kWh of natural gas [1].

The SHC system is compared with a conventional system made by a conventional chiller (10 kW) and a gas boiler (10 kW). During the operation step (25 years), the conventional system consumes 1,995 kWh/year of electricity and 2,882/year kWh of natural gas. It is worth noting that pipes and pumps considered for the SHC system are additional to the ones present in both systems.

To start the tool application, the user have to complete the worksheets 1 and 2 by using the above data.

Table 2. Worksheet 1: SHC system.

Components of the SHC system	Unit of measure	Quantity
Absorption chiller (12 kW)	unit	1
Absorption chiller (19 kW)	unit	-
Adsorption chiller (8 kW)	unit	-
Ammonia	kg	15
Auxiliary gas boiler (10 kW)	unit	1
Auxiliary conventional chiller (10 kW)	unit	1
Cooling tower (32 kW)	unit	1
Evacuated tube collector	m^2	35
Flat plate collector	m^2	-
Glycol	kg	-
Heat storage (2000 l)	unit	1
Heat rejection system (24 kW)	unit	-
Pipes	m	60
Pump (40 W)	unit	8.25
Water	kg	10
Energy sources	**Unit of measure**	**Quantity**
Electricity, low voltage, Italy (including import)	kWh/year	1,117
Natural gas, burned in boiler modulating, <100 kW, Europe	kWh/year	414
Other information	**Unit of measure**	**Quantity**
Useful life of the system	year	25

In detail, Table 2 provides a list of the SHC system components and energy sources[†] included in the LCA tool, and the corresponding quantity inserted by the user for the examined system.

It is important to note that the list refers to components having specific characteristics, e.g. 32 kW cooling tower, 2000 l heat storage, etc.

If the corresponding component for the system under study has a different features, multiple or fractional units should be used to reach the total size. This can happen only when the unit of measure is “unit”.

The worksheet referring to input data for the conventional system is showed in Table 3.

Table 3. Worksheet 2: Conventional system.

Components of the conventional system	Unit of measure	Quantity
Battery lead-acid	kg	
Battery lithium-iron-phosphate	kg	
Battery lithium-ion-manganate	kg	
Battery nickel cadmium	kg	
Battery nickel cobalt manganese	kg	
Battery nickel metal hydride	kg	
Battery sodium-nickel-chloride	kg	
Battery v-redox	kg	
Conventional chiller (10 kW)	unit	1
Electric installation (PV system)	unit	
Gas boiler (10 kW)	unit	1
Inverter (500 W)	unit	
Inverter (2500 W)	unit	
Photovoltaic panel, a-Si	m^2	
Photovoltaic panel, CdTe	m^2	
Photovoltaic panel, CIS	m^2	
Photovoltaic panel, multi-Si	m^2	
Photovoltaic panel, ribbon-Si	m^2	
Photovoltaic panel, single-Si	m^2	
Pipes	m	
Pump (40 W)	unit	
Energy sources	**Unit of measure**	**Quantity**
Electricity, low voltage, Italy (including import)	kWh/year	1,995
Natural gas, burned in boiler modulating, <100 kW, Europe	kWh/year	2,882
Other information	**Unit of measure**	**Quantity**
Useful life of the system	year	25

The next step for using the LCA tool is optional and allows for visualizing default data referring to the specific impacts of components and energy sources for both the systems (worksheets 3 and 4). Data sources of energy and environmental impacts are indicated in the following:

- The impacts of absorption chiller (12 kW), adsorption chiller (8 kW), cooling tower (32 kW), and heat rejection system are referred to [9];
- The impacts of absorption chiller (19 kW) are referred to [6];
- The impacts of electricity, natural gas, ammonia, auxiliary gas boiler, gas boiler, auxiliary conventional chiller, conventional chiller, evacuated tube collectors, flat plate collectors, glycol, heat storage (2000 l), pipes, pump (40 W), water, inverters, electric installation, and photovoltaic panels are referred to [10];
- The impacts of batteries are referred to literature studies [11, 12, 13, 14].

The calculated energy and environmental impacts for the examined systems are displayed in the worksheets 5 and 6. In detail, for each system the LCA results include (Fig.1):

[†] By using a drop-down menu, the tool allows for a selection of electricity in different countries and of natural gas burned in different boilers.

- The total life cycle impact;
- The total impact for each component/energy source;
- A dominance analysis on the life cycle steps (manufacturing, operation and end-of-life) that cause the main energy and environmental impacts (hot spots);
- A dominance analysis on the components that are responsible of the main impacts in the manufacturing and end-of-life step.

The results are also showed with graphs, which visualize the contribution of the different life cycle steps to the total impact, and the incidence of each system's component on the manufacturing and end-of-life steps.

For this case, GER and GWP of the SHC system are about 466 GJ and 28.5 tons of CO2eq, respectively. It can be noted that the operation step is the main contributor towards the GER (73%) and GWP (74%), while the contribution of the end-of-life step is negligible (lower than 1%).

COMPONENTS OF THE SHC SYSTEM	GLOBAL ENERGY REQUIREMENT (GER) (MJ)				GLOBAL WARMING POTENTIAL (GWP) (kg CO_{2eq})			
	Manufacturing	Operation	End-of-Life	Total	Manufacturing	Operation	End-of-Life	Total
Absorption chiller	26005.37	-	3.13	26008.50	1382.34	-	12.55	1394.89
Absorption chiller	0.00	-	0.00	0.00	0.00	-	0.00	0.00
Adsorption chiller	0.00	-	0.00	0.00	0.00	-	0.00	0.00
Ammonia	629.30	-	0.00	629.30	31.44	-	0.00	31.44
Auxiliary gas boiler	6781.86	-	61.51	6843.37	365.71	-	12.04	377.75
Auxiliary conventional chiller	8131.10	-	7.83	8138.93	1550.46	-	25.82	1576.28
Cooling tower	2950.69	-	10.74	2961.43	149.98	-	3.13	153.11
Evacuated tube collector	55289.29	-	454.37	55743.66	3043.85	-	137.94	3181.78
Flat plate collector	0.00	-	0.00	0.00	0.00	-	0.00	0.00
Glycol	0.00	-	0.00	0.00	0.00	-	0.00	0.00
Heat storage	14811.72	-	21.32	14833.04	783.31	-	12.71	796.02
Heat rejection system	0.00	-	0.00	0.00	0.00	-	0.00	0.00
Pipes	3928.98	-	19.92	3948.90	157.98	-	5.82	163.80
Pump	974.95	-	3.09	978.04	57.03	-	0.66	57.69
Water	0.19	-	0.00	0.19	0.01	-	0.00	0.01
Electricity, low voltage, Italy (including import)	-	299835.66	-	299835.66	-	17970.14	-	17970.14
Natural gas, burned in boiler modulating, <100 kW, Europe	-	46393.30	-	46393.30	-	2763.89	-	2763.89
Total	**119503.45**	**346228.96**	**581.90**	**466314.31**	**7522.10**	**20734.03**	**210.67**	**28466.80**

COMPONENTS OF THE CONVENTIONAL SYSTEM	GLOBAL ENERGY REQUIREMENT (GER) (MJ)				GLOBAL WARMING POTENTIAL (GWP) (kg CO_{2eq})			
	Manufacturing	Operation	End-of-Life	Total	Manufacturing	Operation	End-of-Life	Total
Battery lead-acid	0	-	0	0	0	-	0	0
Battery lithium-iron-phosphate	0	-	0	0	0	-	0	0
Battery lithium-ion-manganate	0	-	0	0	0	-	0	0
Battery nickel cadmium	0	-	0	0	0	-	0	0
Battery nickel cobalt manganese	0	-	0	0	0	-	0	0
Battery nickel metal hydride	0	-	0	0	0	-	0	0
Battery sodium-nickel-chloride	0	-	0	0	0	-	0	0
Battery v-redox	0	-	0	0	0	-	0	0
Conventional chiller	8131.10	-	7.83	8138.93	1550.46	-	25.82	1576.28
Electric installation (PV system)	0	-	0	0	0	-	0	0
Gas boiler	6781.86	-	61.51	6843.37	365.71	-	12.04	377.75
Inverter	0	-	0	0	0	-	0	0
Inverter	0	-	0	0	0	-	0	0
Photovoltaic panel, a-Si	0	-	0	0	0	-	0	0
Photovoltaic panel, CdTe	0	-	0	0	0	-	0	0
Photovoltaic panel, CIS	0	-	0	0	0	-	0	0
Photovoltaic panel, multi-Si	0	-	0	0	0	-	0	0
Photovoltaic panel, ribbon-Si	0	-	0	0	0	-	0	0
Photovoltaic panel, single-Si	0	-	0	0	0	-	0	0
Pipes	0	-	0	0	0	-	0	0
Pumps	0	-	0	0	0	-	0	0
Electricity, low voltage, Italy (including import)	-	535516.70	-	535516.70	-	32095.28	-	32095.28
Natural gas, burned in boiler modulating, <100 kW, Europe	-	322960.12	-	322960.12	-	19240.40	-	19240.40
Total	**14912.96**	**858476.81**	**69.34**	**873459.11**	**1916.17**	**51335.67**	**37.86**	**53289.70**

Fig. 1. Results for SHC system (top) and for conventional system (down).

A detailed contribution analysis of each life cycle step shows that the evacuated tube collectors and the absorption chiller cause the main impacts during the manufacturing and end-of-life, and that electricity consumption is the largest contributor during the operation step.

For the conventional system, GER and GWP are about 873 GJ and 53.3 tons of CO_{2eq}, respectively. The incidence of the operation step on the total impacts is about 96-98%. The main contributor to the impacts of the manufactuing step is the conventional chiller (about 54.5% of GER and 81% of GWP), while electricity is the energy source responsible of the main impacts during the operation step. During the end-of-life the main contributor to GER is the gas boiler (about 89%), and to GWP is the conventional chiller (about 68%).

A comparison of GER and GWP of the two examined systems is showed in Fig. 2. For this specific case study and for the selected impact categories, the SHC system has better energy and environmental performances than the conventional system (impacts 47% lower). This occurs because the higher impacts caused by the manufacturing and end-of-life of the SHC system are balanced by the energy savings and avoided emissions during the operation step. Thus, the results of this specific comparison highlight the advantages due to the use of SHC systems in substitution of conventional ones.

System	GLOBAL ENERGY REQUIREMENT (GER) (MJ)				GLOBAL WARMING POTENTIAL (GWP) (kg CO_{2eq})			
	Manufacturing	Operation	End-of-Life	Total	Manufacturing	Operation	End-of-Life	Total
SHC system	119503.45	346228.96	581.90	466314.31	7522.10	20734.03	210.67	28466.80
Conventional system	14912.96	858476.81	69.34	873459.11	1916.17	51335.67	37.86	53289.70

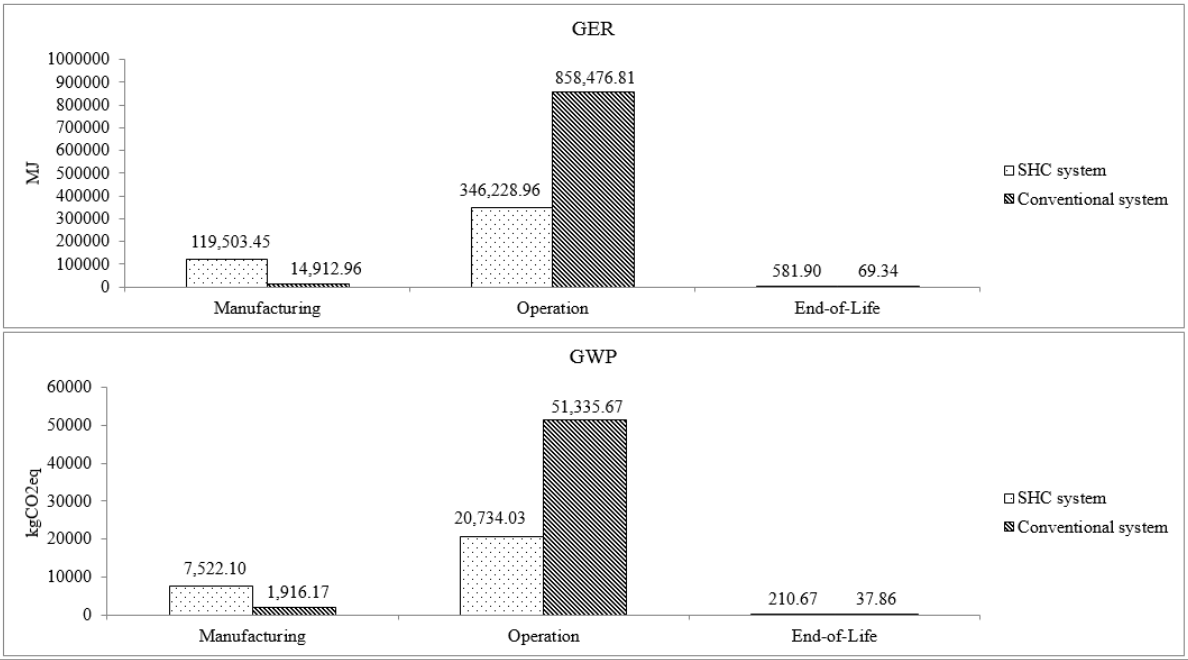

Fig. 2. Comparison of GER and GWP for the SHC and the conventional system.

The last step of the analysis is the calculation of a set of indices (EPT, GWP-PT, and ERR) useful to estimate the time needed to offset the energy consumption and environmental impacts due to the life cycle of a SHC system in substitution with a conventional one.

An analysis of the last worksheet (Fig.3) indicates that EPT and GWP-PT are about 5.1 years and 4.7 years, respectively. These results of the payback indices quantify the net energy and environmental benefits related to the SHC system, despite the larger amount of energy consumption and emissions during its manufacturing and end-of-life.

It is important to highlight that the payback indices values are strongly dependent on the national electricity mix [15]. For example, by changing the electricity mix of Italy (including import), characterized by specif impact to GER of 10.74 MJ/kWh and to GWP of 0.644 kg CO_{2e}q/kWh, with the electricity mix of Austria (including import), characterized by lower specif impacts to GER (9.06 MJ/kWh) and GWP (0.446 kg CO_{2e}q/kWh), the EPT rises from 5.1 years to 5.5 years and the GWP-PT goes from about 4.7 years to about 5.5 years.

The value of ERR is about 4.2. This means that the energy saved during the useful life of the SHC system overcomes the global energy consumption due to its manufacture and end-of-life of about four times.

Energy Payback Time=($GER_{SHC\text{-}system}$-$GER_{Conventional\text{-}system}$)/$E_{year}$			
Energy Payback Time is defined as the time during which the SHC system must work to harvest as much primary energy as it requires for its manufacturing and end-of-life. The harvested energy is considered as net of the energy expenditure for the system use.			
$GER_{SHC\text{-}system}$	=	120,085.35	MJ
$GER_{Conventional\text{-}system}$	=	14,982.30	MJ
E_{year}	=	20,489.91	MJ/year
Energy Payback Time	=	5.13	year

GWP Payback Time=($GWP_{SHC\text{-}system}$-$GWP_{Conventional\text{-}system}$)/$GWP_{year}$			
GWP Payback Time is defined as the time during which the avoided GWP impact due to the use of the SHC system is equal to GWP impact caused during its manufacturing and end-of-life.			
$GWP_{SHC\text{-}system}$	=	7,732.77	$kgCO_{2eq}$
$GWP_{Conventional\text{-}system}$	=	1,954.03	$kgCO_{2eq}$
GWP_{year}	=	1,224.07	$kgCO_{2eq}$/year
GWP Payback Time	=	4.72	year

Energy Return Ratio=$E_{overall}$/$GER_{SHC\text{-}system}$			
Energy Return Ratio represents how many times the energy saving overcomes the global energy consumption due to the SHC system.			
$GER_{SHC\text{-}system}$	=	120,085.35	MJ
$E_{overall}$	=	512,247.85	MJ
Energy Return Ratio	=	4.27	

Fig. 3. Payback indices.

3. Conclusions

A tool able to carry out simplified LCAs and to calculate energy and environmental impacts of SHC systems was proposed in this paper.

The tool was applied to a SHC system located in southern Italy. The results provided a comprehensive investigation of the energy and environmental performance of the systems during its life cycle. In addition, for this specific case study, the analysis showed the energy and environmental advantages due to the use of SHC systems in substitution of conventional ones.

In detail, the higher impacts caused by the SHC system during the manufacturing and end-of-life steps were balanced by the energy savings and avoided emissions during the operation step in a time lower than 5 years, as pointed out from the calculated payback time indices.

The tool presents some limitations, related to the availability of energy and environmental data for few components of the SHC and conventional systems. New data for components and energy sources, which are actually non-available in the scientific literature or in the environmental databases, would be needed for allowing the correct application of the tool to different systems. However, the tool has various advantages, summarized in the following:

- It can be used both by LCA practitioners and non-professional users;
- It is applicable to different geographic contexts by the selection of different electricity mix;
- It allows for the comparison of energy and environmental performances of SHC and conventional systems;
- It enables users to evaluate if there are real benefits due to the installation of a SHC system in substitution of a conventional one;

- It allows for the calculation of the energy and environmental payback time indices due to the additional impact that usually is caused during the manufacturing and end-of-life of the SHC system, if compared with a conventional system.

Finally, it represents an original and easy-to-use tool that enables researchers, designers, and decision-makers to take environmentally sound decisions in the field of SHC technologies.

The tool is freely available on the website of Task 48 of IEA: http://task48.iea-shc.org/.

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