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Life cycle performance assessment of small solar thermal cooling systems and conventional plants assisted with photovoltaics

Marco Beccali [a,*], Maurizio Cellura [a], Pietro Finocchiaro [a], Francesco Guarino [a], Sonia Longo [a], Bettina Nocke [b]

[a] Università degli Studi di Palermo, Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici (DEIM), viale delle Scienze ed.9, 90128 Palermo, Italy

[b] AEE INTEC, Institute for Sustainable Technologies, Feldgasse 19, A-8200 Gleisdor, Austria

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Abstract

Starting from the results of a Life Cycle Assessment of small solar assisted heat driven chillers, the application of such methodology has been extended to systems with a conventional compression chiller assisted by a photovoltaic plant (PV). This study aims to provide a comprehensive compared investigation of these two families of solar assisted cooling systems (with solar thermal or PV). Results indicate that, in many cases, the systems with the PV grid connected plant performed best. In addition, two more configurations were investigated to further define the PV assisted systems, which minimise their interaction with the grid through the use of electricity storages. These systems performed worse than the PV grid connected systems and the solar thermal assisted systems in nearly all the analysed cases.

Keywords: Solar cooling; Life Cycle Assessment; Photovoltaics

1. Introduction

Small solar thermal cooling systems based on heat driven chillers often show contradictory performance that is strongly dependent on design assumptions, correct sizing of the system components and the efficiency of the auxiliary equipment. Good results in terms of electricity and gas savings can be achieved through an accurate design of the system which takes into account climate characteristics and building loads during all the year. When the analysis is extended to the primary energy balances that accounts for the average efficiency of the national electricity production system, additional elements that affect the global performance must be introduced.

A technology as competitive as solar thermal cooling is photovoltaic-based cooling using photovoltaic (PV) panels to generate electricity connected to a conventional water chiller. Recent price drops of PV panels and also the improvement of PV modules and compression chiller performance have paved the way to a wider application of this technology (Cellura et al., 2012). However, while PV assisted solar cooling systems are in many cases very effective in terms of primary energy saving, some concerns still remain when considering the environmental impact related to their life cycle.

The environmental impacts of energy conversion systems can also be assessed by considering the use of energy during their operation and also during the other steps of the life cycle (Ardente et al., 2011; Beccali et al., 2007). A well established and standardised method to fulfil this task is the Life Cycle Assessment (LCA). The LCA also considers the environmental impact of a goods and services while considering the primary renewable and non-renewable energy consumption, resources and materials use and emissions during the entire life cycle. This method is a powerful tool to compare different systems that provide the same service and also optimise processes and components in

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* Corresponding author. Tel.: +39 091 23861911; fax: +39 091 484425.
E-mail address: marco.beccali@unipa.it (M. Beccali).

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complex systems during several phases of their life cycle (Beccali et al., 2013; Cellura et al., 2011).

In the scientific literature, there are numerous studies on the LCA of renewable energy technologies (Battisti and Corrado, 2005; Kannan et al., 2006; Varun et al., 2009). A study that analyses the energy and environmental performance of photovoltaic and solar thermal systems is reported by Beccali et al. (2012). For photovoltaic systems with a stand-alone configuration, Garcìa-Valverde et al. (2009) performed an interesting study that examined a 4.2 kW_p stand-alone solar PV system with polycrystalline panels, operating in the south-east of Spain. This study estimated that there was a primary energy use of 470 GJ and a production of 13.17 tons of CO_2. The largest energy requirements and emissions were related to the construction phase; in particular to the PV modules and batteries.

In the IEA SHC Task 38 framework, a specific activity called the "LCA of solar cooling systems" has been performed to apply this type of analysis to small sized solar H/C systems equipped with adsorption or absorption chillers (Beccali et al., 2010, 2012). Additionally, Task 48, titled "Quality assurance and support measures for Solar Cooling" started in October 2011 is an extension of the Task 38 activities while expanding to a larger set of systems and applications. Starting from these outcomes, the application of LCA has been extended to other systems and climatic regions. This paper presents the results of a LCA study aimed to compare systems with 12 kW absorption chillers to conventional compression chiller systems assisted by a photovoltaic plant. This study aims to provide a more comprehensive investigation of the performance of these two families of solar assisted cooling systems. The main objectives of this study are the assessment of the energy and environmental performance of these systems during their life-cycle, of the energy performance of the systems during the operational phase (considering different configurations and locations). Another relevant objective is the assessment of the primary energy savings and avoided emissions related to the use of these systems instead of conventional ones that are connected to national electric grids.

2. Systems definition

Several system configurations were investigated (see Table 1 and Fig. 1). For solar heating and cooling (SHC) systems based on absorption chillers, this study considered two different options for a summer back-up heat driven system: a "hot back-up" (with a natural gas burner that feeds the absorption chiller generator) and a "cold back-up" (with a conventional compression chiller that integrates the cooling production). Two types of PV assisted systems were also investigated: grid connected and stand-alone systems that both produce all or part of the electricity required for the chillers and auxiliary equipment. For winter heating purposes, all the configurations use a natural gas burner, which is the main source of heat generation in conventional systems and integrates solar thermal collectors heat generation in the SHC ones. As a reference case, a full conventional heating and cooling energy system based on a compression chiller (with nominal cooling energy efficiency ratio (EER) close to 2.5) and a natural gas burner were analysed to be compared to the solar assisted systems.

All the systems were simulated with detailed TRNSYS models for three locations: Palermo (Italy), Zurich (Switzerland) and Rio de Janeiro (Brazil). Three reference buildings (see Table 2), tailored to have the same peak cooling demand (12 kW), have been defined and modelled according to local building practices and regulations.

Fig. 2 shows different climate/load characteristics of the three locations. In Zurich, the heating loads are much larger than the cooling loads. Palermo and Rio de Janeiro show a similar trend in solar radiation, although the cooling loads are much higher in Rio than in Palermo. The climate in Rio is characterised by a nearly homogeneous hot climate during the year, so heating loads are almost zero.

PV systems are sized to generate the electricity required by the chiller and the auxiliaries. For grid connected PV systems, the designed peak power was calculated to generate all the electricity required for one year of cooling system operation.

The stand-alone systems were sized according to two different considerations, related to the average daily electricity load and the production in the months with cooling demand.

In the first case (System 3), the PV generators are designed to meet the average maximum daily deficit for the cooling months. The electric storage ensures three days of autonomy in the cooling period, considering the worst average daily production gap. Thus, in the winter, the system generates a surplus of electricity (approximately 1.7 times the electricity demand for cooling) that can be used by other appliances.

This method is "conventional" for sizing a PV stand-alone system. More detailed methods can be used for the efficient electricity management of grid-connected systems. For example, a household may store its produced energy allowing the electricity provider to switch the connection off during periods of peak demand. Smart grid applications can also be explored. A house can interactively work with the grid and trade with power markets. Peak reduction and demand response can be established more thoroughly with storage than without (Mulder et al., 2010).

Nevertheless, the thermal SHC systems are not able to completely avoid electricity consumption like the PV system (System 3). For System 6, the saved electricity is approximately 48% of the total demand for Palermo and 34% for Zurich and Rio de Janeiro. Most of the residual electricity consumption is used for the auxiliary chiller: 50% for Palermo, 55% for Zurich and 40% for Rio de Janeiro.

To compare systems with similar abilities, while aiming to avoid grid electricity consumption for cooling, a second design method for the PV stand-alone system was

Table 1
Main characteristics of the proposed systems.

	Heating	Cooling
System 1 conventional	Provided by a natural gas burner	Provided by a conventional compression chiller connected to the electricity grid.
System 2 conventional + PV grid	Same as System 1	Provided by a conventional compression chiller. The electricity demand is totally produced by the grid connected PV generator
System 3 conventional + PV stand-alone (full load)	Same as System 1	Provided by a conventional compression chiller. The electricity demand of the system is totally produced by the stand alone PV generator
System 4 Conventional + PV Stand Alone (partial load)	Same as System 1	Provided by a conventional compression chiller. The electricity demand of the system is partially produced by the stand alone PV generator
System 5 solar thermal + absorption with hot back-up	Provided by natural gas burner assisted by a solar thermal system	A solar thermal system (35 m^2) heats water in a thermal storage tank (2 m^3), with a gas burner as integration (hot backup). The water heated in the tank feeds the absorption chiller (12 kW), that is connected in a closed loop with the cooling tower. The building cooling devices are fed by the absorption chiller.
System 6 solar thermal + absorption with cold back-up	Same as System 5	The only difference with system 5 lies in the use of an auxiliary chiller instead of the gas burner for back-up purpose (cold backup)

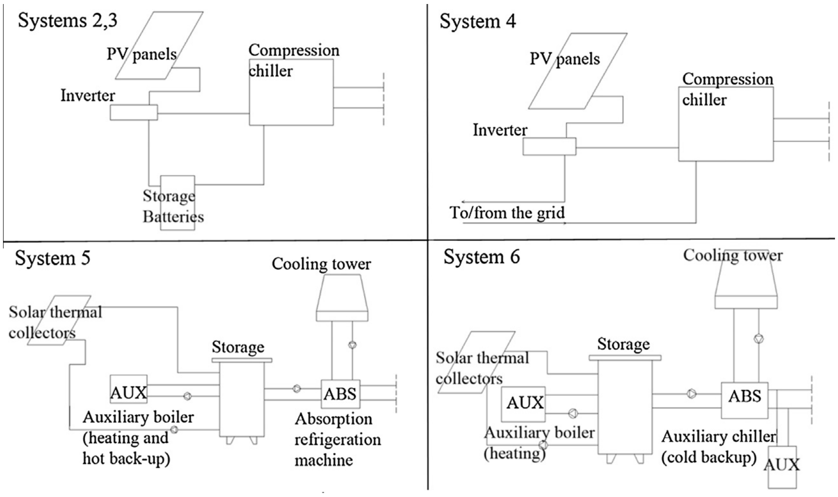


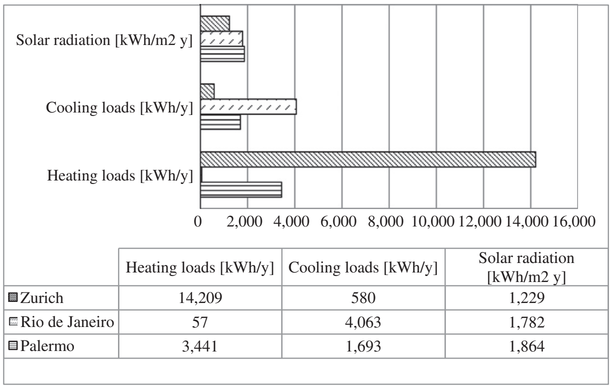
Fig. 1. Schematics of the proposed systems.

Table 2
Characteristics of the three simulated buildings.

	Zurich	Palermo	Rio de Janeiro
Building inertia (kJ/K)	174,735	94,732	94,732
V (m^3)	1120	588	588
S/V (m^2/m^3)	0.47	0.60	0.60
Cooling peak (kW)	12.2	12.6	12.2
Heating peak (kW)	23.5	12.3	2.6
Cooling demand (kW h/y)	2434	3787	9557
Heating demand (kW h/y)	12,794	2924	23

investigated (System 4). In this case the generator peak power was determined such that the yearly production was equal to the electricity saved through the operation of thermal SHC system with cold back-up. The storage capacity still ensured three days of autonomy regarding this fraction of the load.

Results for the PV grid connected and stand-alone sizing are reported in Table 3 and some average performance parameters are described in Table 4.



	Heating loads [kWh/y]	Cooling loads [kWh/y]	Solar radiation [kWh/m2 y]
▨ Zurich	14,209	580	1,229
▭ Rio de Janeiro	57	4,063	1,782
▤ Palermo	3,441	1,693	1,864

Fig. 2. Annual solar radiation on tilted surface (kW h/m^2), cooling and heating loads (kW h) of the three locations studied.

Table 5 shows annual electricity and natural gas consumption for the eighteen combinations of systems/ locations.

The primary energy savings and greenhouse gases emission reductions were demonstrated by comparing the

Table 3
Main characteristics of the proposed PV systems: grid connected (S2), stand-alone full load (S3) and partial load (S4).

	Palermo			Zurich			Rio de Janeiro		
	S2	S3	S4	S2	S3	S4	S2	S3	S4
Peak power (kWp)	1.47	4.41	2.31	1.26	3.15	1.68	3.36	5.25	2.73
Battery capacity (Ah)	0	3360	3360	0	2020	2020	0	3420	3420

Table 4
Mean parameters for the investigated systems.

	Palermo	Zurich	Rio de Janeiro
$COP_{thermal}$ chiller	0.70	0.70	0.69
Seasonal EER electrical chiller (Conventional systems)	2.44	2.33	2.44
Average auxiliary chiller EER (cold backup)	2.40	2.40	2.40
PV Efficiency	11%	11%	11%
Solar collectors efficiency	41%	35%	40%
COP_{el} of the solar thermal system (Hot–cold backup)	4.97–4.24	3.51–3.45	4.97–3.36

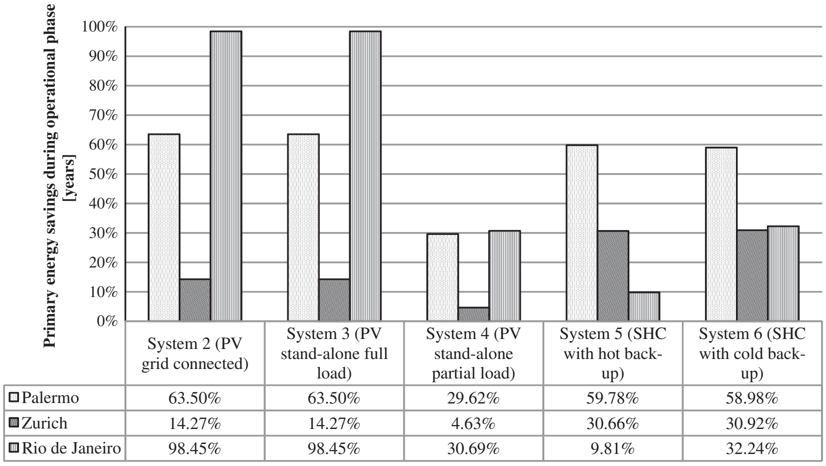
Table 5
Electricity and natural gas consumption for the simulated systems (kW h/y).

		Palermo		Zurich		Rio de Janeiro	
		Heating	Cooling	Heating	Cooling	Heating	Cooling
Conventional (System 1)	Electricity	0	1995	0	1046	0	4542
PV grid-connected (System 2)	Electricity	0	0	0	0	0	0
PV stand alone, full load (Systems 3)	Electricity	0	0	0	0	0	0
PV stand alone, partial load (System 4)	Electricity	0	1065	0	686	0	3005
Systems 1-2-3-4	Natural gas	2754	0	14,951	0	103	0
Hot backup (System 5)	Electricity	52	937	81	655	74	2062
	Natural gas	414	246	10,165	177	0	2956
Cold backup (System 6)	Electricity	52	1065	81	686	74	3005
	Natural gas	414	0	10,165	0	0	0

performance of these innovative systems with those of conventional systems.

For instance, Fig. 3 shows the relative primary energy savings of the operational step (heating and cooling).

It can be noted that all the systems achieve relative savings, in particular PV assisted Systems 2 and 3 in the warmest climates where there is a null or small residual heating load. The worst-performing case is system 4 in Zurich, in which all the PV assisted systems are penalized by the colder climate. Better results are obtained by solar thermal assisted systems (5 and 6), except when high gas consumptions for cooling (System 5) are not compensated by gas savings for heating purposes (i.e. Rio de Janeiro).



	System 2 (PV grid connected)	System 3 (PV stand-alone full load)	System 4 (PV stand-alone partial load)	System 5 (SHC with hot back-up)	System 6 (SHC with cold back-up)
□ Palermo	63.50%	63.50%	29.62%	59.78%	58.98%
▨ Zurich	14.27%	14.27%	4.63%	30.66%	30.92%
▥ Rio de Janeiro	98.45%	98.45%	30.69%	9.81%	32.24%

Fig. 3. Primary energy saving in the operational phase.

When the absolute values of such savings are compared to the other life-cycle sources of energy consumption and pollutant emissions, these considerations must be re-evaluated.

3. Life Cycle Assessment

LCA was applied to the selected systems following an attributional approach[1] and in compliance with the international standards of series 14040 (ISO 14040, 2006; ISO 14044, 2006). Each system was selected as a functional unit, which is a reference unit through which the performance of a product system is quantified in a LCA (ISO 14040, 2006). The energy and environmental impacts were considered for each of the examined systems. The following system boundaries were selected, which define the parts of the life cycle and the processes belong to the analysed system:

- “Production phase”, which includes the supply of raw materials, production/assembly and maintenance/substitution of the main components of the plant.
- “Operational phase”, assumed to last 25 years, which includes the life cycle of the energy sources (electricity and natural gas) consumed (from the grid) during the useful life of the plant. According to the attributional approach, the surplus of electricity generated by PV systems (3 and 4) was not accounted as credits of energy and emissions. In the attributional approach the above credits are usually allocated to the life-cycle of the product or service that consumes the electricity surplus, and not to the life-cycle of the investigated system.
- The end-of-life phase, which includes the treatment of waste from the plant components.

The following phases were not considered, owing to the lack of data:

- Transportation of the plant components from their production sites to the plant.
- Transportation of the plant components from the plant to the disposal site at the end-of-life.
- Installation and minor maintenance steps.

However, their energy and environment impact can be considered negligible (Ardente et al., 2004, 2005; Kalogirou, 2004).

The system components were analysed, as listed below:

- Solar thermal H/C systems: absorption chiller (12 kW), working fluid (water–ammonia), solar thermal collectors, storage tank, cooling tower, supplementary pipes and distribution devices, back-up devices (gas burner and compression chiller for the “cold back-up” configuration).
- Solar PV H/C system: PV polycrystalline modules, inverter, cables and storage for the grid connected configuration; for the stand alone configuration, and lead acid batteries and charge regulators were assumed in addition to the above-mentioned components.
- Conventional systems: compression chiller and gas burner.

The energy and environmental impacts of Systems 1-5-6 are based on Beccali et al. (2012) for Zurich and Palermo, while those for Rio de Janeiro have been calculated. The LCA software SimaPro (PRè, 2012) and the environmental database Ecoinvent (Frischknecht et al., 2007) have been used to assess the energy and environmental impacts for the other systems. Data related to manufacturing and battery disposal and charge regulators were based on Garcìa-Valverde et al. (2009).

The life cycle of each system component was estimated to be 25 years, except for batteries (8.3 years), charge regulators (8.3 years) and inverters (12.5 years).

- The main energy and environmental indexes for assessing the performances of the investigated systems are: Global Energy Requirement (GER), that is the primary energy demand during the life cycle, expressed in MJ.
- Global Warming Potential (GWP), expressed in kg of equivalent CO_2, which 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 carbon dioxide (US EPA, 2011).
- Energy Payback Time (EPT), defined as the time (years) during which the system must work to harvest as much energy as required to offset its production and disposal.
- Emission Payback Time (EMPT), defined as the time (years) during which the cumulative avoided emissions, due to the application of the innovative plant, are equal to those released during the life cycle of the plant itself (years).

GER and GWP impacts were calculated using the Cumulative Energy Demand and EPD 2008 impact assessment methods (PRè, 2012), respectively.

4. Discussion of the results

The calculated GER and GWP values for each system and for each life cycle step are reported in Tables 6 and 7.

A comparison of the GER and the GWP calculated for both the solar assisted H/C systems and the conventional ones is provided in Figs. 4 and 5. System 2 is the best system with the lowest primary energy requirement for the two hottest locations (Palermo and Rio de Janeiro), which also has lower energy requirements than the SHC systems (5 and 6). This result cannot be extended to Zurich, where

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[1] Attributional LCA: inventories the inputs and outputs flows of all processes of a system as they occur (European Union, 2010).

Table 6
Total values of GER for the six systems in three locations.

		System 1	System 2	System 3	System 4	System 5	System 6
Palermo (MJ)	Production	14,357	55,048	667,046	612,529	117,000	129,505
	Operation	845,485	308,616	308,616	595,051	340,029	346,860
	End-of-life	29	78	26,656	26,618	464	476
	Total	859,871	363,743	1,002,319	1,234,198	457,493	476,841
Zurich (MJ)	Production	14,357	50,088	420,347	381,937	119,101	131,605
	Operation	1,954,272	1,675,426	1,675,426	1,863,795	1,355,121	1,350,068
	End-of-life	29	75	16,058	16,035	464	476
	Total	1,968,658	1,725,588	2,111,831	2,261,767	1,474,686	1,482,149
Rio de Janeiro (MJ)	Production	14,357	103,383	696,382	629,784	117,000	129,505
	Operation	744,880	11,543	11,543	516,241	671,816	504,699
	End-of-life	29	107	27034	26988	464	476
	Total	759.266	115.033	734.959	1.173.013	789.280	634.679

Table 7
Total values of GWP for the six systems in the three locations.

		System 1	System 2	System 3	System 4	System 5	System 6
Palermo (kg CO_{eq})	Production	2497	4442	21,680	19,242	6878	9271
	Operation	50,322	18,025	18,025	35,248	20,322	20,779
	End-of-life	44	129	330	221	346	385
	Total	52,863	22,596	40,035	54,711	27,545	30,435
Zurich (kg CO_{eq})	Production	2497	4194	14,687	12,959	6981	9374
	Operation	101,669	97,855	97,855	100,392	70,370	69,476
	End-of-life	44	118	244	173	346	385
	Total	104,209	102,167	112,786	113,524	77,697	79,235
Rio de Janeiro (kg CO_{eq})	Production	2497	6773	22,915	19,924	6878	9271
	Operation	32,721	674	674	22,752	34,246	22,078
	End-of-life	44	225	374	243	346	385
	Total	35,261	7672	23,963	42,919	41,469	31,735

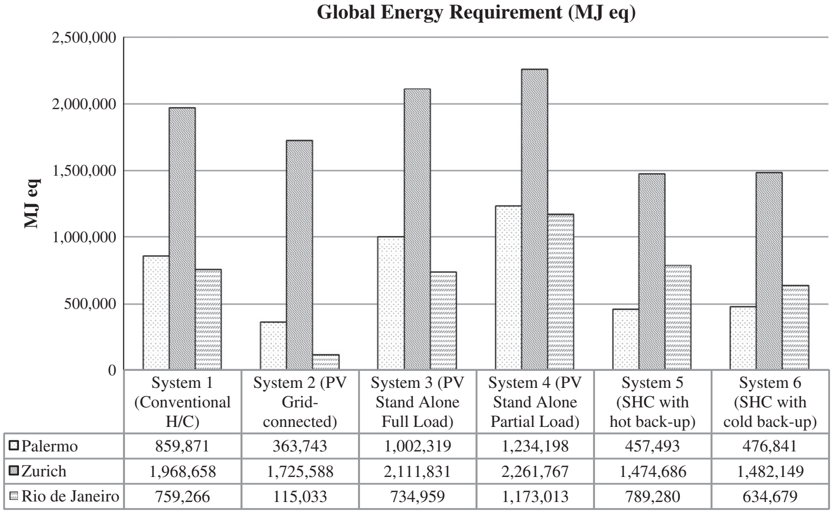
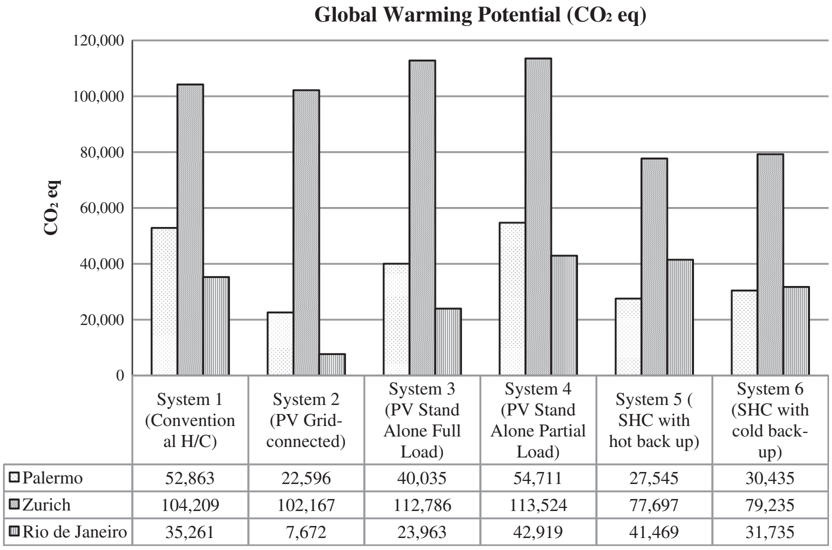


Fig. 4. Total values of GER (MJ) for the six systems in the three locations.

the relevant winter heating loads cause high natural gas consumption far larger than the electricity savings. The SHC systems perform better than the PV stand-alone Systems 3 and 4 for all the locations except for Rio de Janeiro, where System 3 has a slightly lower GER than System 5. In this case, System 5 also has a slightly higher GER than the conventional H/C system. In all the other cases, Systems 3 and 4 have a higher GER than System 1. Similar considerations are obtained from the GWP figures except for the fact that System 3 always performs better than the conventional H/C system and, only for Rio de Janeiro, it also is better than the SHC systems (5 and 6).



	System 1 (Conventional H/C)	System 2 (PV Grid-connected)	System 3 (PV Stand Alone Full Load)	System 4 (PV Stand Alone Partial Load)	System 5 (SHC with hot back up)	System 6 (SHC with cold back-up)
▢ Palermo	52,863	22,596	40,035	54,711	27,545	30,435
▨ Zurich	104,209	102,167	112,786	113,524	77,697	79,235
▨ Rio de Janeiro	35,261	7,672	23,963	42,919	41,469	31,735

Fig. 5. Total values of GWP (kg CO_{2equiv}) for the six systems in the three locations.

From an analysis of the results in Tables 5 and 6, the operation phase is the main contributor towards the GER (72.7–99.3%) and GWP (68.3–97.5%). These data from the three steps of the system's life explain the reason for the higher GER and GWP values of System 4 (PV stand alone with a partial load) if compared to those of System 3 (PV stand alone with a full load). The highest electricity consumption due to the PV area under-sizing compensates for the benefits of the lower impact of the production phase. Additionally:

- For Palermo System 3 (PV full load): the production step provides the highest contribution to GER (66.5%) and GWP (54%) due to the high impacts of the batteries and PV modules. The operation step has an incidence ranging from 31% for the GER and 45% for the GWP due to the use of natural gas for heating.
- For Palermo System 4 (PV partial load): the production and operation steps have an incidence on the GER of approximately 49.6% and 48.2%, respectively. The higher incidence on the GWP (64.4%) is related to the operation step and is caused by the residual electricity that is not provided by the PV system.
- For Rio de Janeiro System 2 (PV grid connected): the production step has the largest impact on the GER (89.9%) and GWP (88.3%), mainly due to the PV modules. The low incidence of the operation step is due to the low natural gas consumption for heating and the negligible electricity consumption.
- For Rio de Janeiro System 3 (PV full load): because of the manufacturing of the batteries and the low consumption of natural gas during the operation step, the incidence of the production step is approximately 95% of the total GER and GWP.
- For Rio de Janeiro System 4 (PV partial load): the production step provides 53.7% of the GER and the 46.4% of the GWP, while the operation step is responsible for 44% of the GER and 53% of the GWP.

Further analysis of the GER shares for the production step of the systems equipped with the PV panels (Table 8) shows that:

- For System 2 (PV grid connected), the higher contribution to the primary energy consumption is due to the production of the PV modules (ranging from 57.6% for Zurich to 74.4% for Rio de Janeiro) and chiller (ranging from 13.89% for Rio de Janeiro to 28.66% for Zurich). The inverter has an incidence of approximately 8%.
- For Systems 3 and 4 (PV Full and partial load), the largest impacts on the GER are connected to battery manufacturing and substitutions during the system's life (76–79% for System 3 and 82–85% for System 4) and PV modules (15–17% and 8.5–10% of the GER for Systems 3 and 4, respectively). The other components impact for less than 3.5%.

As outlined above, the authors did not take into account the energy and environmental benefits arising from the surplus of electricity produced by PV systems. However, in order to obtain a more solid analysis, the authors estimated the avoided energy and environmental impacts arising from the use of electricity generated by PV as substitution of electricity generated by the national energy mix (see Table 9).

The payback times highlight the impacts related to the GER and GWP values, which can be recovered during the life of the systems from the generated yearly savings. Figs. 6 and 7 show the values for the EPT and EMPT, respectively.

EPTs and EMPTs results obtained for Palermo and Zurich are quite similar between each other for Systems

Table 8
Production phase GER, for all the proposed systems.

	Palermo	Zurich	Rio		Palermo	Zurich	Rio
	GER % (production phase)				GER % (production phase)		
System 1				*System 5*			
Conventional chiller	87.09%	87.09%	87.09%	Absorption chiller	23.98%	23.56%	23.98%
Gas boiler	12.91%	12.91%	12.91%	Solar collectors	50.78%	49.89%	50.78%
				Heat storage	13.00%	12.77%	13.00%
System 2				Cooling tower/heat rejection	2.54%	2.50%	2.54%
PV modules	61.11%	57.56%	74.37%	Gas boiler	1.58%	1.56%	1.58%
Inverter	7.47%	8.21%	7.54%	Glycol (Zurich)	0%	1.76%	0%
Cables and wirings	1.98%	1.86%	2.41%	Piping and insulation	7.18%	7.05%	7.18%
Gas boiler	3.37%	3.70%	1.79%	Pumps	0.94%	0.92%	0.94%
Chiller	26.08%	28.66%	13.89%				
				System 6			
System 3				Absorption chiller	21.67%	21.32%	21.67%
PV modules	15.13%	17.15%	17.25%	Solar collectors	45.88%	45.15%	45.88%
Inverter	1.70%	0.90%	1.94%	Heat storage	11.74%	11.56%	11.74%
Cables and wirings	0.49%	0.50%	0.56%	Cooling tower/heat rejection	2.29%	2.26%	2.29%
Battery	78.88%	79.50%	76.59%	Gas boiler	1.43%	1.41%	1.43%
Charge regulator	1.37%	1.40%	1.33%	Glycol (Zurich)	0%	1.60%	0%
Gas boiler	0.28%	0.30%	0.27%	Piping and insulation	6.49%	6.38%	6.49%
Chiller	2.15%	2.20%	2.06%	Pumps	0.85%	0.83%	0.85%
				Conventional chiller	9.66%	9.50%	9.66%
System 4							
PV modules	8.63%	10.07%	9.92%				
Inverter	1.05%	1.08%	1.02%				
Cables and wirings	0.28%	0.33%	0.32%				
Battery	85.90%	82.85%	84.69%				
Charge regulator	1.49%	1.44%	1.47%				
Gas boiler	0.30%	0.49%	0.29%				
Chiller	2.34%	3.76%	2.28%				

Table 9
Energy and environmental benefits arising from the surplus of electricity produced by PV systems.

	GER (MJ/year)	NRE (MJ/year)	GWP (kg CO_{2eq}/year)
System 4 – Zurich	6005	5186	81
System 4 – Palermo	16,412	15,057	978
System 3 – Zurich	23,208	20,043	313
System 3 – Rio	18,891	5842	826
System 3 – Palermo	49,921	45,799	2974

2, 5 and 6. In these two locations these systems show the best EPT: around 5 years for SHC and 2–3 years for PV grid connected. These are the best performance among the investigated configurations.

Systems 3 and 4, in all the investigated sites, and System 5 in Rio de Janeiro show EPTs nearly higher than 25 years (the life time of the systems). This is due to systems having GER or GWP higher than the values of the conventional systems.

The PV grid connected is always the best system, including Rio de Janeiro and also for the EMPT figures. The only exception is in Zurich where EMPT is relatively high (11.6 years) and much higher than the values associated to the SHC systems. The main reason behind these results can be traced in the greenhouse gas emissions related to winter heating.

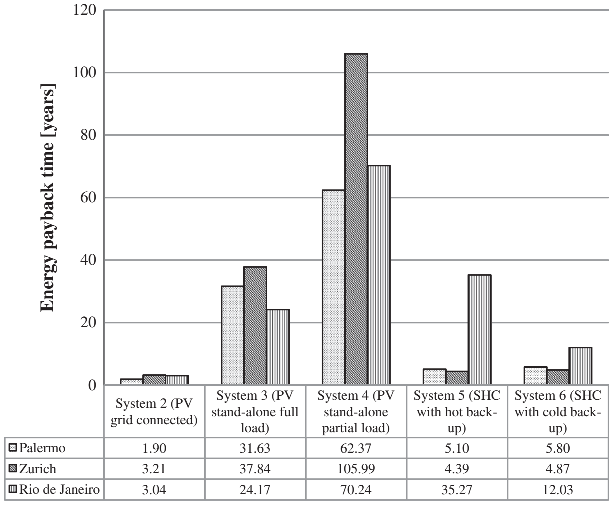
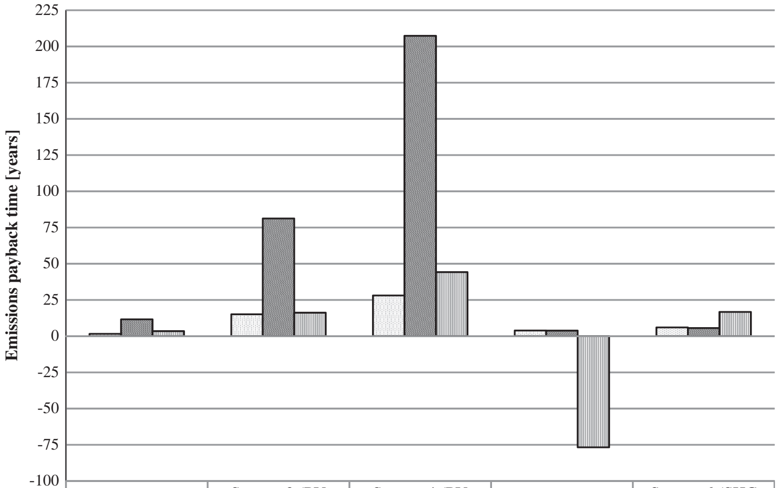


Fig. 6. Energy Payback Times (EPT) for the solar assisted systems.

For instance, in Zurich, EMPT is approximately 200 years for System 4 and 81 for System 3 due to the small difference between the GWP and GER during the operation step for the conventional system and for the PV stand-alone systems.

Considering the payback indexes for Rio de Janeiro, only System 2 has low EPT and EMPT values, approximately 3 years each. The other configurations have EPT values ranging from 12 years (System 6, cold back-up)



	System 2 (PV grid connected)	System 3 (PV stand-alone full load)	System 4 (PV stand-alone partial load)	System 5 (SHC with hot back-up)	System 6 (SHC with cold back-up)
□ Palermo	1.57	15.07	28.06	3.90	6.02
▨ Zurich	11.61	81.21	207.32	3.82	5.61
▤ Rio de Janeiro	3.48	16.19	44.21	-76.77	16.72

Fig. 7. Emissions payback time (EMPT) for the solar assisted systems.

to 35 years (System 5, hot back-up). The last value is strongly dependent on the energy performance of the national energy mix. This dependency can be assessed through a sensitivity analysis by changing the global national electricity efficiency from 0.565 MJ_{el}/MJ_{prim} to 0.327 MJ_{el}/MJ_{prim} (the electricity efficiency of Switzerland) (Frischknecht et al., 2007; PRè, 2012). Thus, the EPT would be reduced to 12 years for System 5 and 6.4 for System 6 (cold back-up).

The EPT values for the stand alone systems (3–4) are high, approximately 22–24 years. This range would be reduced to 16–18 years if only one battery substitution (instead of two) is required during the life cycle or by adopting more environmentally friendly technologies.

The EMPT in Rio de Janeiro ranges from 16 to 44 years for both the stand alone systems and is around 17 years for System 6 (Cold back-up). A negative EMPT value is obtained for System 5 (hot back-up) due to a GWP value for the operation phase that is higher than the conventional system, which is a result of the electricity mix efficiency in Brazil. Although the conventional plant consumes more electricity, it releases less greenhouse gas emissions than System 5 (hot back-up), which requires a large consumption of natural gas for the absorption chiller back-up.

5. Conclusions

This study compares five solar assisted H/C systems energy and environmental performance to conventional ones by means of the LCA methodology. Three of these systems are assisted by PV plants (Systems 2-3-4) while two are based on the use of absorption cooling coupled with a solar thermal system (Systems 5-6).

Results are very sensitive to climate conditions affecting the energy performance in the operation phase, and to the national electricity mix.

It can be noted that, in all the investigated climates, the systems with the PV grid connected plant show the best performance, as they have low GER and GWP values and payback times. The only exception is in Zurich, where SHC systems perform better. It is also worth noting that this plant-typology is very different, in terms of equipment mass and related impacts from the other plants because it does not require any kind of energy storage (including electricity) due to free interaction with the grid. For these reasons, a comparison of this system with the other ones is not solid enough because the strength of the SHC system is the ability to reduce the dependence from the electric grid and to avoid peaks, overloads and power quality variations. A similar capability is assigned to PV assisted plants by defining two more configurations, which minimise their interaction with the grid through the use of electricity storages. Aiming to analyse a PV system with similar storage capacity as a solar thermal assisted one, a system providing the same electricity load that is avoided by the solar thermal systems is defined (called "partial load"). As well, another system, able to produce the total electricity demand required by chiller and auxiliary equipment is investigated (called "full load"). The "partial load" system performance are always worse than the "full load" and both of these systems perform worse than the PV grid connected system in terms of EPT and EMPT. This confirms that the negative impact of electricity storage manufacturing is so large that only more efficient, durable and "green" storage technologies can overcome it.

The results of this study indicate that solar thermal assisted systems are the best systems in terms of life-cycle energy and environmental performance among the ones having a storage capability (including "full" and "partial" load PV assisted) in nearly all the analysed cases.

Contradictory results, however, are obtained for Rio de Janeiro, where the large cooling demand during the whole year is not adequately supported by solar radiation availability. Additionally, the large average national electricity conversion efficiency makes it difficult for SHC plants to be competitive, especially the ones with hot back-up (using natural gas), providing an opportunity for PV stand-alone assisted systems. This is true when considering the GWP performance. In fact, in Brazil electricity production is characterised by a high use of renewable energy sources. For this reason in some cases, the conventional systems (mainly using electricity for cooling) show better performance than the solar assisted ones.

In a cold climate (Zurich), the opportunity to extend the use of the solar thermal system to meet the high heating load ensures good system performance (in particular for the hot back-up). This statement cannot be extended for PV assisted systems as well, which do not save on natural gas.

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