ECO-DESIGN OF SOLAR DRIVEN SYSTEMS: A PERFORMANCE COMPARISON BETWEEN THE ITALIAN AND THE BRAZILIAN CONTEXT

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ABSTRACT

The paper shows a comparative analysis of the performances of two typologies of solar assisted cooling systems for building applications. In particular, Life Cycle Assessment (LCA) methodology is applied to assess the energy and environmental impacts of solar-assisted, heat-driven chillers and conventional compression chillers driven by grid-connected and stand-alone photovoltaic configurations.

LCA is applied in compliance with the international standards of ISO 14040. System boundaries are defined following a "cradle to grave" approach, taking into account all the life-cycle phases including the raw materials supply, the production of the components of the plant, the operation and maintenance, and the end-of-life.

The operation step of the assessed systems is simulated with TRNSYS models. Two reference buildings are modeled for two different sites, Palermo (Italy) and Rio de Janeiro (Brazil), according to local practices and regulations. The building models are normalized to have the same peak cooling demand (12 kW).

The results show that the assessed energy and environmental performances of the grid-connected systems are usually better than the others for both climates, while the manufacturing process of storages in the stand-alone configurations does not allow these solutions to be competitive yet. Furthermore, the impact of the high average national electricity conversion efficiency in Brazil on the results is analyzed and discussed.

KEYWORDS

Choosing by advantages, Energy production system design, Environment, Life Cycle Assessment, solar cooling.

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INTRODUCTION

Thermo-hygrometric comfort is an important objective for the indoor environment that designers must consider in the construction of buildings. Even though ‘passive buildings’ have become more common in the last decades, most of the building sector is in need of conditioning plants. In the context of lean buildings, an important topic is minimizing the generation of energy waste in the design phase by selecting the most appropriate system configuration based on the climate and infrastructure of the selected site.

Renewable energy technologies (RETs) can reduce the use of fossil fuels and the related environmental impacts for building air conditioning. However, RETs cannot be considered totally clean because they have energy and environmental impacts that cannot be neglected during their life cycle (Beccali et al. 2012a).

A well established and standardized method to take into account resource use (raw materials and energy) and environmental burdens related to the life-cycle of a technology is the Life Cycle Assessment (LCA): the LCA approach, at least on a concept level, is close to the lean idea of going to the “Gemba”, from the Japanese word meaning “The real place”. LCA investigations can help decision makers to evaluate energy and environmental advantages of a given technology in a specific climate. This method is a powerful tool to compare different systems that provide the same service and also optimize processes and components in complex systems during several phases of their life cycle (Beccali et al. 2012b). Such a tool is useful when trying to select the most ‘lean’ system, while identifying environmental burdens and impacts in detail for every step of the life-cycle from the cradle to the grave: like for the “Gemba” it means to obtain details by visualizing problems, displaying wastes and possible improvements of a manufacturing process.

Starting from the outcomes of research developed within the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Task 38, “LCA of solar cooling system” and the IEA SHC Task 48 “Quality assurance and support measures for Solar Cooling”, the authors extended the application of LCA to other systems and climatic regions (Beccali et al. 2010).

In detail the LCA is applied to compare SHC systems with 12 kW absorption chillers and conventional plants constituted by a compression chiller assisted by photovoltaic panels (PV) to generate electricity.

LIFE CYCLE ASSESSMENT

GOAL AND SCOPE DEFINITION

The goal of the study is to investigate the life-cycle energy and environmental performances of two families of solar assisted cooling plants. Systems with 12 kW absorption chillers and systems with a compression chiller assisted by a PV plant are investigated and compared to a reference conventional system including a gas burner and a compression chiller.

Furthermore primary energy savings and avoided emissions related to the use of these systems are assessed in comparison with the conventional one. Different configurations of the systems are examined as well as their installation in two different locations: Palermo (Italy) and Rio de Janeiro (Brazil).

The analysis is developed applying the LCA methodology, in compliance with the international standards of series ISO 14040 (ISO 14040 2006, ISO 14044, 2006).

Functional unit

The functional unit (FU) is defined as "quantified performance of a product system for use as a reference unit" (ISO 14040 2006). In this study, each examined system is selected as functional unit.

The following FUs are examined:

- FU 1: conventional plant, including a natural gas burner to provide heat and a conventional compression chiller connected to the grid to provide cooling;
- FU 2: conventional plant where all the yearly electricity required by the chiller is produced by a grid-connected photovoltaic generator;
- FU 3: conventional plant where all the electricity needed by the chiller is produced by a stand-alone photovoltaic generator. PV generators are built to meet the 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;
- FU 4: conventional plant where a fraction of the electricity requested by the chiller is produced by a stand-alone photovoltaic system. The generator peak power is determined so that the yearly production is equal to the electricity saved through the operation of thermal SHC systems with cold back-up. The storage capacity still ensures three days of autonomy regarding this fraction of the load;
- FU 5: SHC system, comprising a gas burner for heating purposes and an absorption chiller able to cover cooling loads. The gas burner has also the role of auxiliary heater, being the "hot back-up" of the solar assisted plant;
- FU 6: SHC system, comprising a gas burner for heating purposes and an absorption chiller driven system for cooling. An auxiliary compression chiller is included in the plant for back-up purposes ("cold back-up").

Each SHC system (FU 5 and 6) is composed of a solar thermal collectors system (35 m^2) that heats water collected in a thermal storage tank ($2m^2$). The absorption chiller is connected in a closed loop with a cooling tower.

System boundaries

The system boundaries included in the investigation are:

- production phase, that includes supplying of raw materials and production/assembly of the main components of the plant;
- operation phase, that includes the life-cycle of the energy sources (electricity and natural gas) consumed (from the grid) during the useful life time of the plant. The operation phase of the systems is simulated with TRNSYS 16.1 (University of Wisconsin 2006). The TRNSYS models are fit to have the same

cooling peak demand (around 12 kW) both in Palermo (Italy) and Rio de Janeiro according to local technical practices and regulations. The surplus of electricity generated by PV systems is not counted as credits of energy and emissions;

- the end-of-life phase, that includes the treatment of waste from the plant components.

Installation and minor maintenance, transportation of the plant components from their production sites to the plant and from the plant to the disposal site at the end-of-life are not considered, due to lack of detailed data for these steps. However, their impact on global energy and the environment is likely negligible (Ardente et al. 2005, Kalogirou 2004, Kalogirou 2009).

Data quality and life cycle inventory

According to the general framework provided by ISO 14040, the inventory analysis is carried out to quantify the environmentally significant inputs and outputs of the studied systems, by means of a mass and energy balance of each FU.

The eco-profiles of FUs 1, 5 and 6 are based on Beccali et al. (2012) for Palermo, while the eco-profiles for Rio de Janeiro are calculated according to the Ecoinvent database (Frischknecht et al. 2007). Data related to manufacturing and battery disposal and charge regulators are based on Garcìa-Valverde et al. (2009). The life cycle of each system component was estimated to be 25 years, except for batteries (~8 years), charge regulators (~8 years) and inverters (~12.5 years).

The energy and environmental indexes selected to illustrate investigated system performance are:

- Global Energy Requirement (GER), which represents the entire primary energy demand that arises in connection with every life-cycle step of an economic good (product or service). The index is expressed in terms of MJ;
- Global Warming Potential (GWP), 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 a trace gas expressed relative to that from 1 kg of carbon dioxide. The index is expressed as kg of CO_2 equivalent and is referred to a period of 100 year, that means considering the climate forcing effect over 100 years form the instantaneous release (US EPA 2001).
- Energy Payback Time (EPT), which is defined as the time (years) during which the system must work to harvest as much energy as is required for its life-cycle, including production, use and disposal (Ardente et al. 2005);
- Emission Payback Time (EMPT), which is 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) (Ardente et al. 2005).

GER and GWP impacts are calculated using the Cumulative Energy Demand and EPD 2008 impact assessment methods (IEC 2008, PRè 2010), respectively.

Life cycle impact assessment

We present the GER and GWP for all the proposed systems and for each life-cycle step in order to assess the most 'lean' systems in the selected locations.

A comparison of GER and GWP of the solar assisted H/C systems with those of the conventional ones is provided in Figures 1 and 2.

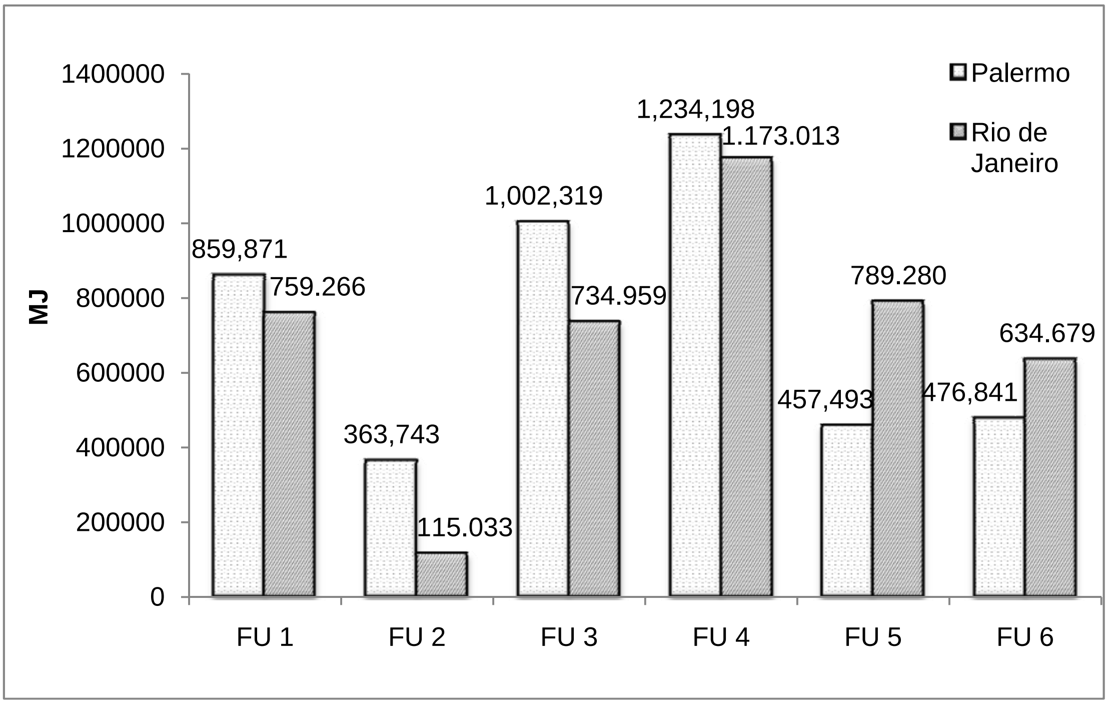


Figure 1: GER (Gross energy) of the examined FUs

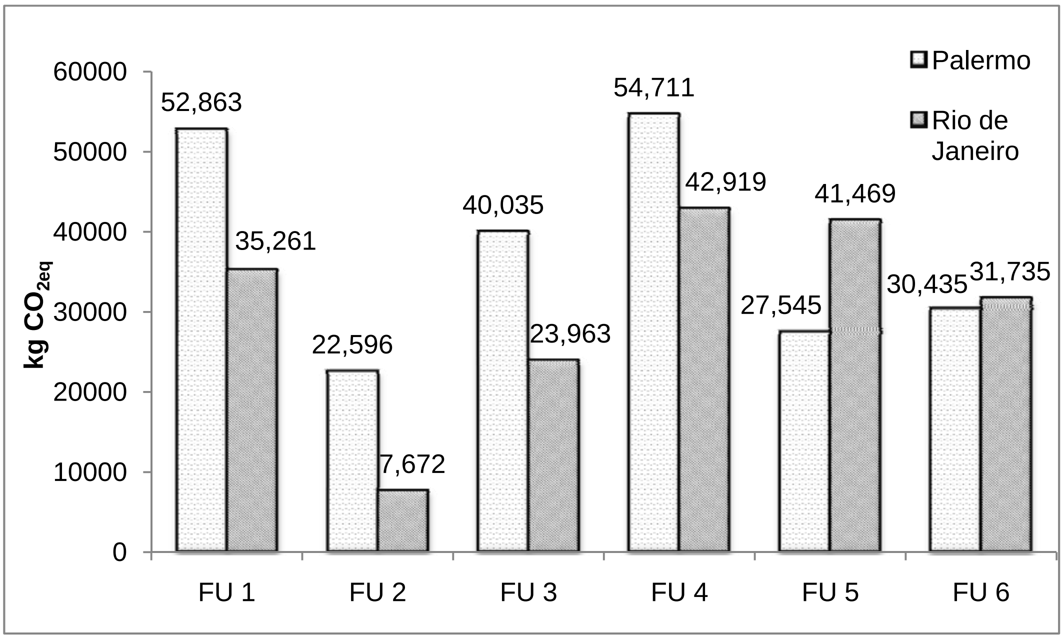


Figure 2: GWP of the examined FUs

FU 2 is the best system with the lowest primary energy requirement for both Palermo and Rio de Janeiro. The SHC systems performed better than the PV stand-alone systems in Palermo than in Rio de Janeiro, where FU 3 has a lower GER than FU 5. In this case, FU 5 also has a higher GER than the conventional H/C system (FU1). In all the other cases, FU 3 and 4 have a higher GER than FU 1. The same considerations can be obtained from GWP figures.

From an analysis of the results in Tables 1 and 2, generally, the operation step is the main contributor towards GER and GWP. These data show that FU 4 (PV stand alone with a partial load) has higher GER and GWP values than FU 3 (PV stand alone with a full load). The highest electricity consumption due to under-sizing of the PV collector area compensates for the benefits of the lower impact of the production phase.

Table 1: GER of the examined FUs for each life-cycle step

		FU 1	FU 2	FU 3	FU 4	FU 5	FU 6
Palermo (MJ)	Production	14,357	55,048	667,046	612,529	117,000	129,505
	Use	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
Rio de Janeiro (MJ)	Production	14,357	103,383	696,382	629,784	117,000	129,505
	Use	744,880	11,543	11,543	516,241	671,816	504,699
	End-of-life	29	107	27,034	26,988	464	476
	Total	759,266	115,033	734,959	1,173,013	789,280	634,679

Table 2: GWP of the examined FUs for each life-cycle step

		FU 1	FU 2	FU 3	FU 4	FU 5	FU 6
Palermo (kg CO_{2eq})	Production	2,497	4,442	21,680	19,242	6,878	9,271
	Use	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
Rio de Janeiro (kg CO_{2eq})	Production	2,497	6,773	22,915	19,924	6,878	9,271
	Use	32,721	674	674	22,752	34,246	22,078
	End-of-life	44	225	374	243	346	385
	Total	35,261	7,672	23,963	42,919	41,469	31,735

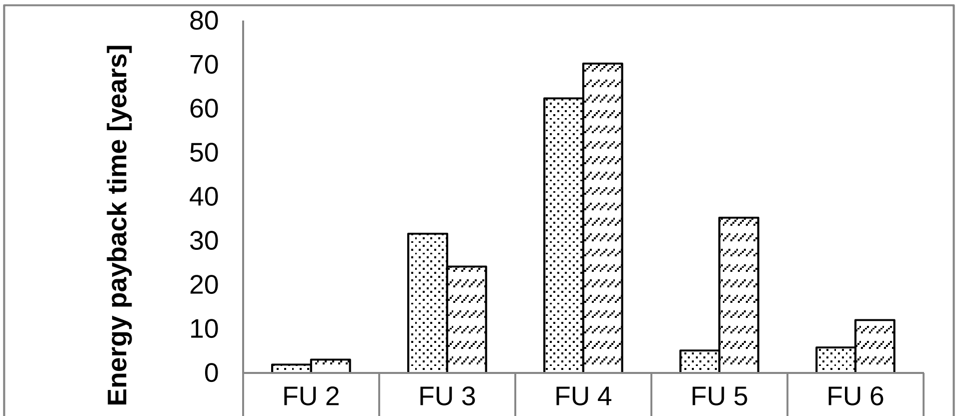
Additionally:

- for Palermo FU 3: 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 GER and 45% for GWP due to the use of natural gas for heating;
- for Palermo FU 4: the production and operation steps have an incidence on GER of approximately 49.6% and 48.2%, respectively. The higher incidence

on 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 FU 2: the production step has the largest impact on 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 FU 3:due to the presence of batteries in the system together with a 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 FU 4: the production step provides 53.5% of GER and the 46.6% of GWP, while the operation step is responsible for 44% of GER and 53% of GWP;
- for FU 2, the higher contribution to the primary energy consumption is due to the production of the PV modules (74.4% for Rio de Janeiro) and chiller (13.9% for Rio de Janeiro). The inverter has an incidence of approximately 8%;
- for FUs 3 and 4, the largest impacts on the GER are related to battery manufacturing and substitutions during the system's life (75-79% for FU 3 and 82-85% for FU 4) and PV modules (15-17% and 8.5-10% of the GER for FUs 3 and 4, respectively). The other components have an incidence level less than 3.5%.

The energy and emission payback times highlight the impacts related to GER and GWP values, which can be recovered during the life of the systems from the generated yearly savings. Figure 3 shows the calculated values for the first of these indicators (EPT). Considering the FUs 2-5-6 EPT in Palermo ranges from 1.9 years (FU 2) to 5.8 years (FU 6); the EMPT (Figure 4) varies instead from about 1.6 years for FU 2 to about 28 years for FU 4.



	FU 2	FU 3	FU 4	FU 5	FU 6
Palermo	1,897	31,633	62,368	5,098	5,796
Rio de Janeiro	3,038	24,171	70,240	35,270	12,032

Figure 3: EPT for the selected FUs

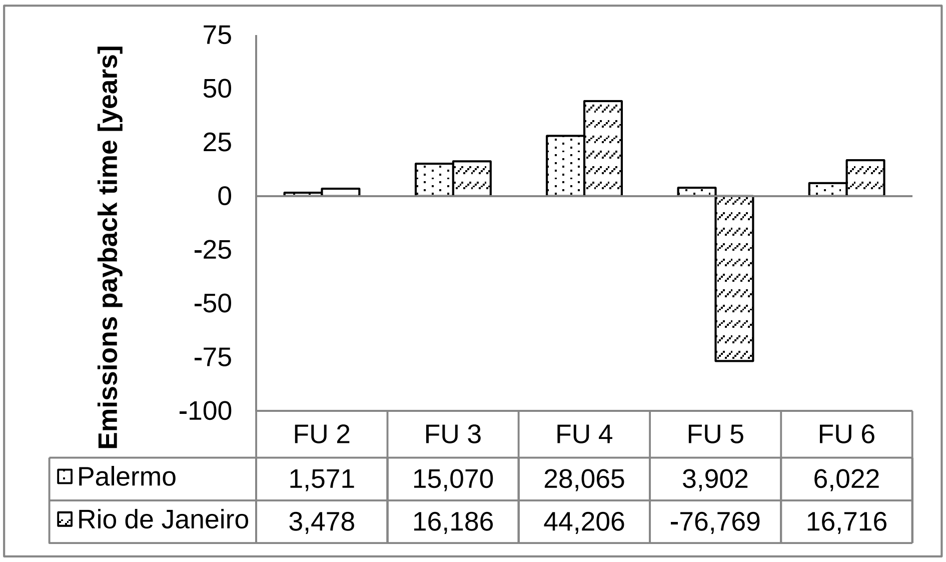


Figure 4: EMPT for the selected FUs

Considering the payback indexes for Rio de Janeiro, only FU 2 has low EPT and EMPT values, approximately 3 years each. The other configurations have EPT values from about 12 years (FU 6) to about 35 years (FU 5). The EPT values for the stand alone systems are high, (24 and 70). This range can be reduced 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 about 16 to 44 years for both the stand alone systems and is around 17 years for FU 6. A negative EMPT value is obtained for FU 5 due to a GWP value 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 FU 5, which requires a large consumption of natural gas.

DISCUSSION

The described approach aims to choose the best alternative among the six proposed in accordance to the 'waste minimization' thinking and to the impact the climate has on the thermal plant performances and on the building loads. All the plants are sized to offer the same output, that is the 12 kW peak heating/cooling power, but generate different amount of energy, need to operate for different amount of time (different climate and site) and are characterized by a different amount of energy required for their manufacturing process (different plant layout) and operation phase. As it is clearly identifiable in all the figures shown in the paper, the behavior of the proposed systems show s a deep connection to the site and, therefore need to answer different needs for different users, between Italy and Brazil.

The LCA analysis has allowed a deep understanding of the core processes of the manufacturing of the plants' components, assessing in detail their energy and environmental costs. A lean construction way of thinking would suggest that there is nothing worse than an efficient process, if that process is not necessary. For the case presented in the paper, as the manufacturing and end-of-life phases are based on literature data and the operation phase on TRNSYS simulations, the leanest approach in the design choice is to choose the solution that would need less energy for its whole life-cycle. For grid connected application the lowest energy requirement (GER) is connected to the grid connected PV-assisted (F.U. 2) system, that would reduce energy waste by nearly 75% for the Italian context, and by around ten times in the Brasilian context if compared to the most impacting solution (F.U. 4).

CONCLUSIONS

The importance of the lean construction of conditioning system in a lean building design has been stressed in the presented paper, comparing energy and environmental performances of a conventional system with five solar assisted systems. Three of these solar assisted systems are integrated with PV plants while two are based on the use of absorption chiller coupled with a solar thermal system.

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

The results show that the PV grid-connected conventional system is characterized by the lowest primary energy requirement and GWP for both the examined climates.

Solar thermal assisted systems result to be the best systems among the ones having a storage capability in nearly all the analysed cases.

With regards to the PV assisted systems, the PV grid connected ones perform better than the PV systems with electrical storage. The impact of storage manufacturing is large so only more efficient, durable and "green" technologies can overcome this impact. For the two PV stand alone systems, the system that provides the same electricity load that is avoided by the solar thermal systems has worse performances than the system that is able to produce the total electricity demand (chiller plus auxiliary equipment).

Contradictory results are obtained for Rio de Janeiro, where there is a large cooling demand during all months, which is not adequately supported by solar radiation availability. Additionally, the large average national electricity conversion efficiency makes it difficult for solar thermal H/C plants to be competitive, providing an opportunity for PV stand alone assisted systems. Additionally, in Brazil, when considering the GWP values and that electricity production is characterised by a high use of renewable energy sources, in many cases, the conventional systems are more convenient than the solar assisted ones.

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