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# Life Cycle Assessment performance comparison of small solar thermal cooling systems with conventional plants assisted with photovoltaics

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**Abstract**

Life Cycle Assessment (LCA) allows for the consideration of energy consumption and environmental impacts associated with all the stages of a product's life, *from the cradle to the grave*. Starting from the results obtained in the IEA SHC Task 38 framework for the LCA 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. This study aims to provide a more comprehensive investigation through a comparison of these two families of solar assisted cooling systems (with solar thermal or PV), which is an important topic for studies concerning the research of effective and environmentally friendly systems that exploit solar radiation for cooling and heating purposes. In hot climates, the systems with the PV grid connected plant performed best. Anyway, a comparison of this system with the other systems is not meaningful because the strength of the solar thermal H/C system is the ability to reduce the dependence from the electric grid and to avoid peaks, overloads and power quality variations. Thus, 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

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## 1. Introduction

Small solar cooling systems based on heat driven chillers often show contradictorily performance that is strongly dependent on the design assumptions, correct sizing of the system components and the actual efficiency of the auxiliary equipment. A comparison with conventional cooling plants that is based on compression chillers technology, can improve our understanding of the chiller's cooling COP, a key parameter of the energy efficiency of the systems. When the analysis is extended to the primary energy balances while considering the average efficiency of the electricity production system, additional elements that affect the global performance must be introduced. Thus, the technology (or the combination of technologies) for electricity generation is important. Additionally, 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. 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 good/service while considering the primary 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 complex systems during several phases of their life cycle.

In the scientific literature, there are numerous studies on the LCA of renewable energy technologies [1], [2], [3]. A study that analyses the energy and environmental performances of photovoltaic and solar thermal systems is reported by Beccali et al. [4]. For photovoltaic systems with a stand alone configuration, Garcìa-Valverde et al. [5] 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 a primary energy use of 470 GJ and 13.17 tons of $CO_2$ emissions. The largest energy requirements and emissions are related to the construction phase; particularly, the PV modules and batteries.

In the IEA SHC Task 38 framework, a specific activity called the "LCA of solar cooling system" has been performed to, for the first time, apply this type of analysis to small size solar H/C systems equipped with adsorption or absorption chillers [4], [6]. Additionally, task 48, "Quality assurance and support measures for Solar Cooling", started in October 2011, and is an extension of this activity that applies to a wider 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 an LCA study aimed to compare systems with 12 kW absorption chillers with systems with a conventional compression chiller assisted by a photovoltaic plant. This study aims provide a more comprehensive investigation of the performances of these two families of solar assisted cooling systems, which is important for studies concerning effective systems to exploit solar energy for cooling purposes.

The basic objectives of this study are to estimate the energy and environmental performances of the systems during their life-cycle, the energy performances of the systems during the use phase (considering different configurations and locations) and the primary energy savings and avoided emissions related to the use of these systems instead of conventional systems that are connected to national electric grids.

## 2. Systems definition

Several system configurations have been investigated (see table 1). For SHC systems based on absorption chillers, this study considered two different options for a summer season 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 typologies 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 systems use a natural gas burner, which is coupled with solar thermal collectors in the first two configurations. As a reference case, a full conventional heating and cooling energy system based on a compression chiller (with nominal cooling COP = 2.5) and a natural gas burner have been analysed for comparison with the solar assisted systems.

Table 1. Main characteristics of the proposed systems

| | Heating | Cooling |
|---|---|---|
| System 1<br>Conventional | Provided by a natural gas burner. | Provided by a conventional compression chiller connected to the electricity grid. |
| System 2<br>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<br>Conventional + PV Stand alone (full load) | Same as System 1 | Provided by a conventional compression chiller. The electricity demand of systems is totally produced by the stand alone PV generator |
| System 4<br>Conventional + PV Stand Alone (partial load) | Same as System 1 | Provided by a conventional compression chiller. The electricity demand of systems is partially produced by the stand alone PV generator |
| System 5<br>Solar Thermal + Absorption with Hot back-up | Provided by natural gas burner assisted by a solar thermal system. | A solar thermal system (35m$^2$) heats water in a thermal storage tank (2m$^3$), 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<br>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) |

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

Figure 1 shows different climate/load characteristics associated with 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 homogeneous hot climate during the year, so heating loads are nearly zero.

Generally, PV systems are built to produce the electricity required by the chiller and the auxiliaries. For grid connected PV systems, the designed peak power was calculated to produce all the electricity required for one year of cooling system operation. The stand alone systems have been built with two different considerations, which both include the average daily electricity load and the production in the months with cooling demand.

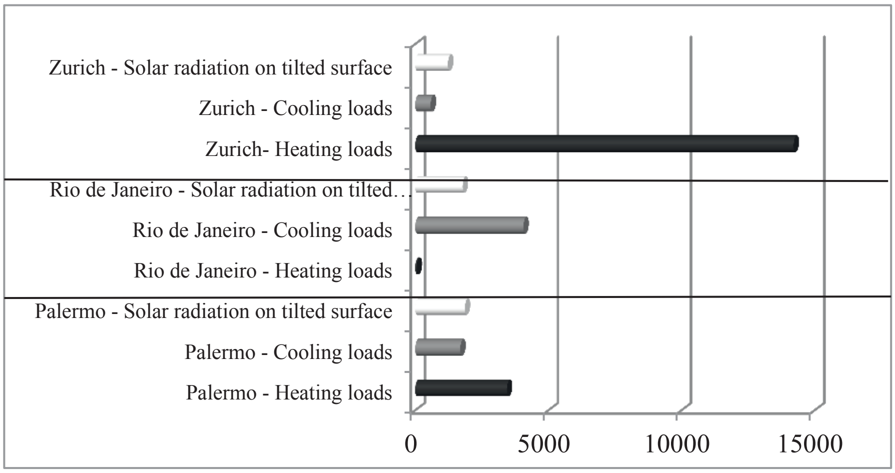

Fig. 1. Annual solar radiation on tilted surface [kWh/m$^2$], cooling and heating loads [kWh] of the three chosen locations

In the first case (System 3), the PV generators were 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 utilised by other appliances.

This method is "conventional" for sizing a PV stand alone system. More precise methods can be used for efficient electricity management for systems that can be connected to the grid. For example, a household can store its produced energy allowing the electricity provider to switch it 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 [7].

This work do not aims to optimise PV stand alone sizing; 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% Rio de Janeiro.

Aiming to compare systems with similar capabilities to avoid grid electricity consumption for cooling, this study used a second design method for the PV stand alone system (System 4). For this system, the generator peak power was 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.

Results of PV grid connected and stand alone sizing are reported in Table 2.

Table 2. 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 | 3360.9 | 3360 | 0 | 2020.1 | 2020 | 0 | 3417.1 | 3420 |

Table 3 shows electricity and natural gas consumption for the eighteen combinations of systems/locations.

Table 3. Electricity and natural gas consumption for the simulated systems [kWh]

| | | Palermo | | Zurich | | Rio de Janeiro | |
|---|---|---|---|---|---|---|---|
| | | Heating | Cooling | Heating | Cooling | Heating | Cooling |
| Conventional (System 1) | Electricity | 0 | 1,995 | 0 | 1,046 | 0 | 4,542 |
| PV grid-connected (System 2);<br>PV stand alone, full load (Systems 3) | Electricity | 0 | 0 | 0 | 0 | 0 | 0 |
| PV stand alone, partial load (System 4) | Electricity | 0 | 1,065 | 0 | 686 | 0 | 3,005 |
| | Natural gas | 2,754 | 0 | 14,951 | 0 | 103 | 0 |
| Hot backup (System 5) | Electricity | 52 | 937 | 81 | 655 | 74 | 2,062 |
| | Natural gas | 414 | 246 | 10,165 | 177 | 0 | 2,956 |
| Cold Backup (System 6) | Electricity | 52 | 1,065 | 81 | 686 | 74 | 3,005 |
| | Natural gas | 414 | 0 | 10,165 | 0 | 0 | 0 |

The primary energy savings and greenhouse gases emission reductions were demonstrated by comparing the use of these innovative systems with conventional systems. These results are reported and discussed in the next chapter together with other LCA application results to highlight the impacts of the systems and components during the different life phases.

## 3. Life Cycle Assessment

LCA was applied to the selected systems in compliance with the international standards of series 14040 [8], [9]. The energy and environmental impacts were considered for each of the examined systems. The following system boundaries were included:

- the production phase includes supplying raw materials, production/assembly and maintenance/ substitution of the main components of the plant;
- the use phase 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 end-of- life phase includes the treatment of waste from the plant components.

The following steps were not considered:

- 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.

The system components were analysed, as listed below:

- solar thermal H/C systems: absorption chiller (12 kW), work 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, lead acid batteries and charge regulators in addition to the above-mentioned components;
- conventional systems: compression chiller and gas burner.

The eco-profiles of systems 1-5-6 were based on Beccali et al. [4] for Zurich and Palermo, while the eco-profiles for Rio de Janeiro were calculated. For the other systems, the LCA software SimaPro [10] and the environmental database Ecoinvent [11] were used to construct the eco-profiles. Data related to manufacturing and battery disposal and charge regulators were based on Garcìa-Valverde et al. [5].

- 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 were:
- Global Energy Requirement (GER), which represents the entire primary energy demand in the life cycle and it is expressed in MJ;
- Global Warming Potential (GWP), in Kg of equivalent $CO_2$;
- 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 production and disposal;
- 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).

GER and GWP impacts were calculated using the Cumulative Energy Demand and EPD 2008 impact assessment methods [10], respectively.

## 4. Results of the discussion

The calculated GER and GWP values for each system and for each life cycle step are reported in Tables 4 and 5 and Figures 2 and 3.

Table 4. 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 | 661,380 | 609,317 | 117,000 | 129,505 |
| | Operation | 845,485 | 308,616 | 308,616 | 595,051 | 340,029 | 346,860 |
| | End-of-life | 29 | 78 | 26,649 | 26,614 | 464 | 476 |
| | Total | 859,871 | 363,743 | 1,002,319 | 1,234,198 | 457,493 | 476,841 |
| Zurich (MJ) | Production | 14,357 | 48,032 | 416,449 | 379,881 | 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 | 70 | 16,053 | 16,030 | 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 | 99,486 | 689,636 | 655,483 | 117,000 | 129,505 |
| | Operation | 744,880 | 11,543 | 11,543 | 516,241 | 671,815 | 504,699 |
| | End-of-life | 29 | 102 | 27,027 | 26,984 | 464 | 476 |
| | Total | 759,266 | 115,033 | 734,959 | 1,173,013 | 789,280 | 634,679 |

Table 5. 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 | 2,497 | 4,442 | 21,680 | 19,242 | 6,878 | 9,271 |
| | 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 | 2,497 | 4,194 | 14,687 | 12,959 | 6,981 | 9,374 |
| | 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 | 2,497 | 6,773 | 22,915 | 19,924 | 6,878 | 9,271 |
| | Operation | 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 |

A comparison of the GER and the GWP of the solar assisted H/C systems with those of the conventional ones is provided in Figures 2 and 3. System 2 was the best system with the lowest primary energy requirement for the two hottest locations (Palermo and Rio de Janeiro), which also had lower energy requirements than the SHC systems (5 and 6). The SHC systems performed better than the PV stand alone systems 3 and 4 for all the locations except for Rio de Janeiro, where System 3 has a lower GER than System 5. In this case, System 5 also has a higher GER than the conventional H/C system. In all the other cases, Systems 3 and 4 have a higher GER than System 1. The same considerations are obtained from the GWP figures.

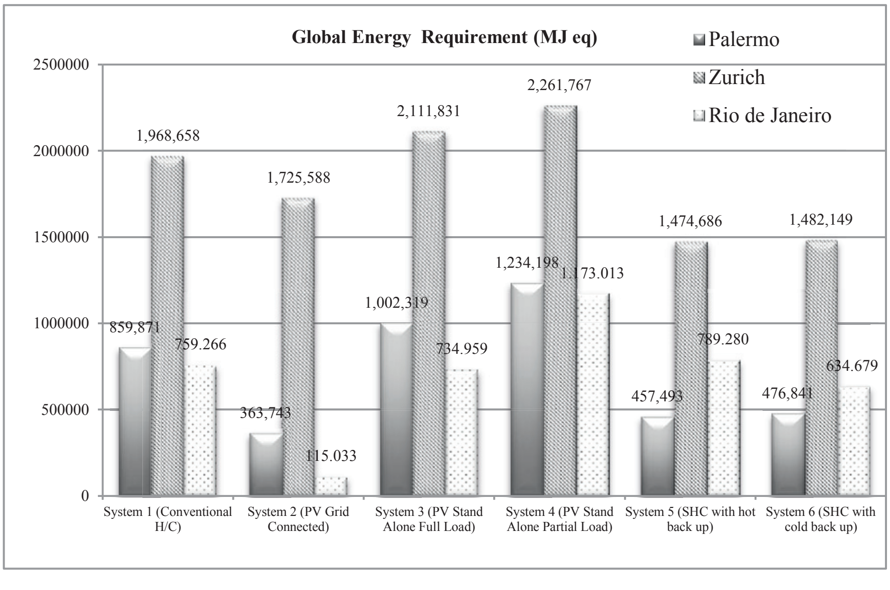

Fig. 2. Total values of GER (MJ) for the six systems in the three locations

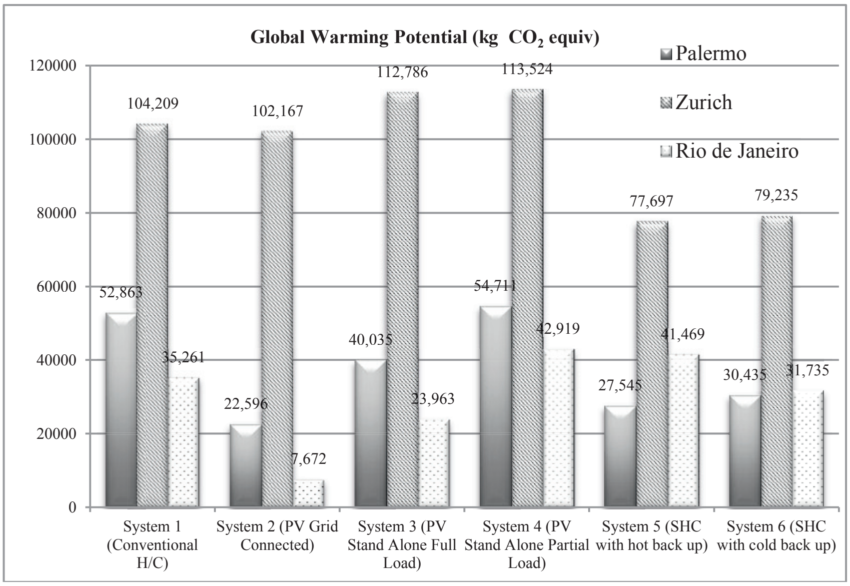

Fig. 3. Total values of GWP (kg $CO_{2\ equiv}$) for the six systems in the three locations

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

- for Palermo System 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 the GER and 45% for the GWP due to the use of natural gas for heating;
- for Palermo System 4: 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 the residual electricity that is not provided by the PV system;
- for Rio de Janeiro System 2: 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: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 System 4: the production step provides 53.5% of the GER and the 46.6% 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 (see Figure 4) reveals:

- for System 2, 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 13.9% for Rio de Janeiro to 28.7% for Zurich). The inverter has an incidence of approximately 8%;

- for Systems 3 and 4, the largest impacts on the GER are related to battery manufacturing and substitutions during the system's life (75-79% 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 have an incidence level less than 3.5%.

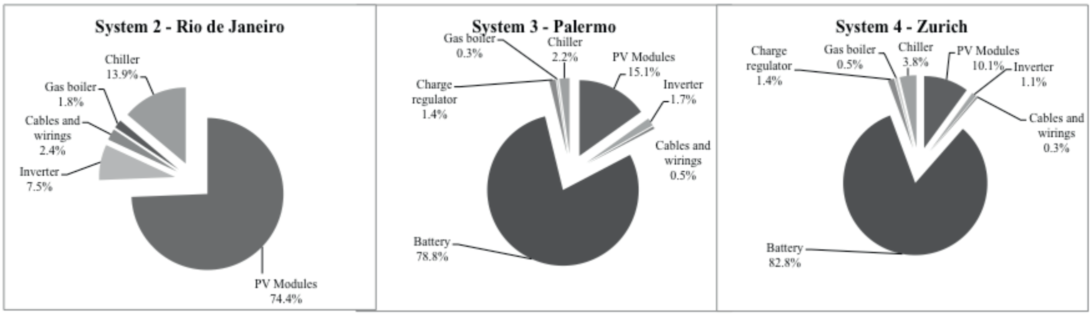

Fig. 4. Production step for systems equipped with PV modules: incidence of the components on GER for (a) Rio de Janeiro, (b) Palermo and (c) Zurich

The energy and emission 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. Figure 5 shows the calculated values for the first of these indicators (EPT).

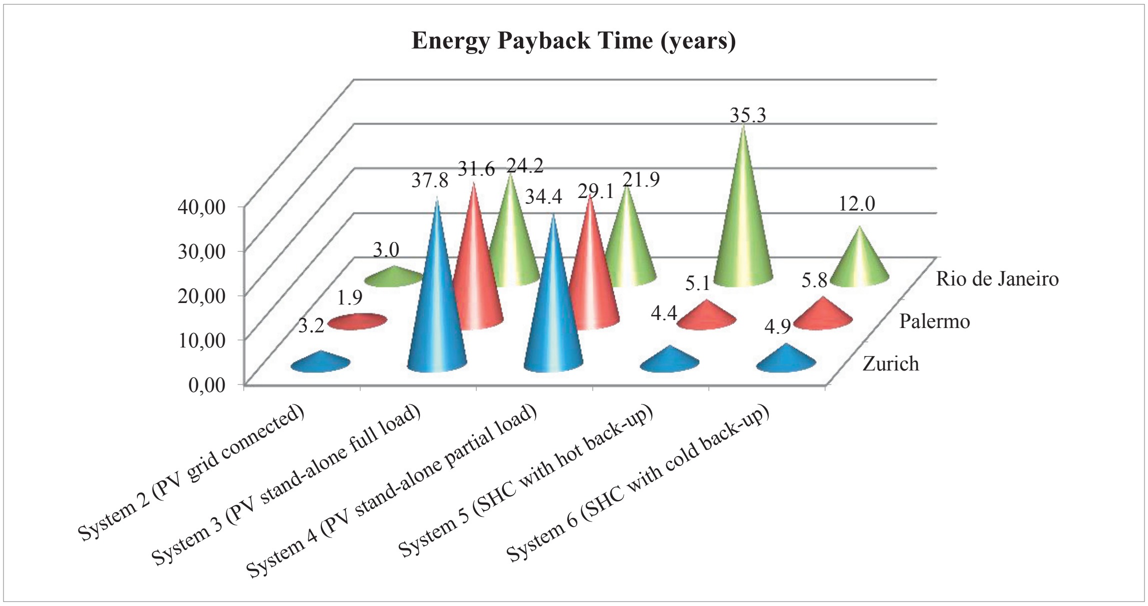

Figure 5: Energy Payback Times for the solar assisted systems

Results obtained for Palermo and Zurich were quite similar in terms of EPT. Considering the Systems 2-5-6 EPT ranges from 1.9 years (System 2) to 5.8 years (System 6) in Palermo, and from 3.2 years (System 2) to 4.9 years (System 6) in Zurich.

An EPT variable from 29 years to 38 years was obtained for the stand alone systems in the above localities.

In Palermo, the EMPT varies from 1.6 years for System 2 to 28 years for System 4. In Zurich, this indicator varies from 3.8 years for system 5 to 81 years for System 3 and to approximately 200 years for System 4.

This last value is due to the small difference between the GWP 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 from 12 years (System 6) to 35 years (System 5). The last value is strongly dependent on the energy performance of the national energy mix. This value can be assessed with a fast sensitivity analysis by changing the global national electricity efficiency from the actual value of 0.565 $MJ_{el}/MJ_{prim}$ to 0.327 $MJ_{el}/MJ_{prim}$ (the electricity efficiency of Switzerland) [10], [11]. Thus, the EPT would be reduced to 12 years for System 5.

The EPT values for the stand alone systems are high, approximately 22-24 years. This range can 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 28 years for System 6. A negative EMPT value was obtained for System 5 due to a GWP value that was higher than the conventional system (see Figure 3), 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, which requires a large consumption of natural gas.

## 5. Conclusions

This study compares five solar assisted H/C systems with LCA methodology. Three of these systems are assisted by PV plants while two are based on the use of absorption cooling coupled with a solar thermal system. In hot climates (Palermo and Rio de Janeiro), the systems with the PV grid connected plant performed best, as they have low GER and GWP values and payback times. This plant-type is different than the other plants because it does not require storage due to free interaction with the grid. For these reasons, a comparison of this system with the other systems is not meaningful because the strength of the solar thermal H/C system is the ability to reduce the dependence from the electric grid and to avoid peaks, overloads and power quality variations. Thus, 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. 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 provided the same electricity load that was avoided by the solar thermal systems performed worse than the system that was able to produce the total electricity demand (chiller plus auxiliary equipment). The reduction of the impact in production resulted in the highest residual electricity consumption. Select contradictory results were 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 performances and that electricity production is characterised by a high use of renewable energy sources, in many cases, the conventional systems were more convenient 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 performances. This relationship is not true for PV assisted systems, which do not save on natural gas. However, the obtained results are sensitive to the data [12] from the life cycle inventory for the PV systems [4], [5], [6]. This sensitivity was especially highlighted in the EPT figures for the grid connected PV system. The authors suggest further investigating data sources to produce a sensitivity analysis for the LCA results to improve the data quality.

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