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ENERGY AND ENVIRONMENTAL PERFORMANCES OF SMALL AND INNOVATIVE SOLAR COOLING SYSTEMS

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ABSTRACT: The development of renewable energy technologies is a critical tool for reducing climate change and the reliance on fossil fuels. However, renewable energy technologies cannot be considered totally clean because they require energy consumption and have environmental impacts that cannot be neglected during their life cycle. This paper presents the results of two researches related to the application of solar thermal system for building heating and cooling. It is focused on small and compact systems of two different typologies. An innovative compact Solar DEC system is analysed in terms of potential competitor of stand alone electrically driven HVAC systems. The performances of small absorption chillers coupled with low temperature solar collectors is investigated by the means of Life Cycle Assessment approach in order to highlight their environmental impacts also during manufacturing and end-of-life phases.

Keywords: Solar Heating and Cooling, Energy Saving, Life Cycle Assessment

1 INTRODUCTION

Research on renewable energy systems must be focused either on optimisation of primary energy saving during their utilisation either on the minimisation of the global environmental impact during their life.

The Solar Desiccant and Evaporative Cooling (DEC) technology is an interesting and fascinating solution for applications in building air conditioning. It is a thermally driven open cooling cycle based on evaporative cooling and adsorption processes. In a solar desiccant cooling cycle, solar energy is used to regenerate a desiccant material that dehumidifies moist air by vapour adsorption; the resulting dry and warm air is cooled in a sensible heat exchanger (usually rotating) and then in an (direct) evaporative cooler.

By associating different elementary treatments in moist air (dehumidification, sensible cooling and evaporative cooling) both in the process and exhaust air, the technique uses water as a refrigerant and mostly solar energy as driving heat. In a solar autonomous DEC system, electricity is only used in the auxiliaries, so the technique is environmentally friendly. If the pure DEC effect is not sufficient to guarantee indoor air conditions for the specific application, a hybrid DEC – conventional cooling cycle can be used by adding one or more traditional cooling coils connected with an electric water refrigerator to the standard DEC cycle [1].

In some recent studies, the energy performances of the DEC systems have been investigated, but a few cases have mentioned energy savings in comparison to a conventional air handling unit (AHU) [2] [3].This is due to the fact that auxiliaries consumption often prevails on the achievable saving granted by the solar thermal contribution. 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. 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 [4].

The environmental impacts of energy conversion systems must be assessed by considering the use of energy during their operation and also during the other steps of the life cycle [5], [6]. A well established and standardised method to fulfil this task is the Life Cycle Assessment (LCA). The LCA also considers the environmental impact of goods and services while considering the primary renewable and non-renewable energy consumption, resources and materials use and emissions during the entire life cycle [7].

2 ENERGY PERFORMANCES OF INNOVATIVE COMPACT SOLAR AIR CONDITIONING

Nowadays DEC systems are present on the market only for medium scale air conditioning applications. This is due to the fact that the concept on which large DEC units are based is not suitable for small applications in terms of costs, space and typical restrictions related to the installation of a centralized air system. In common DEC systems, desiccant rotors are normally used. However, the adsorption process realized by means of desiccant rotors presents the disadvantage of causing a temperature increase of the desiccant material. This phenomena is caused by the release to the process air of adsorption heat due to water condensation in the desiccant material and by the carry-over of heat stored in the desiccant material from the regeneration section to the process section.

Moreover, desiccant rotor technology doesn’t present the opportunity to store adsorption capacity into the desiccant material since adsorption rotors are generally built to host a relatively low mass of adsorbent. Therefore, the only option for energy storage can be related to the driving fluid, i.e. water heated by a solar plant. In addition, the use of hot air as regeneration fluid is suitable only with systems without storage.

An innovative patented compact solar air conditioner designed for ventilation, dehumidification and cooling (heating in winter is also possible) is presented [8]. The system is mostly designed for air conditioning of under - roof spaces and can be configured to be installed both on flat and sloped roofs. The system is basically composed by a casing which comprises a solar air collector, two adsorption beds, an integrated cooling tower, two plate wet heat exchangers, fans and all other auxiliaries needed to realize the air handling process.

The system is mainly based on the use of two fixed packed desiccant beds of silica gel, operating in a batch process, and two wet evaporative heat exchangers connected in series. The adsorption bed is a fin and tube heat exchanger, commonly used in several air conditioning applications wherein the spaces between the fins are filled with silica gel grains. Therefore, the adsorption material can be cooled by means of the water loop of heat exchanger which is in connection with an heat sink. In addition, the component can be seen as a latent energy storage since an high adsorption capacity can be accumulated into the desiccant material when solar radiation is available and used it later when cooling energy is needed.

A system of air dumpers provides the commutation between the two adsorption beds in order to guarantee a continuous dehumidification process. For a detailed description of the component and its performances, refer to [8].

A cooling tower which is integrated in the system is used to reject the adsorption heat generated in the desiccant bed operating in dehumidification mode. Regeneration is carried out using a solar air collector. The air flow rate passing the adsorption bed is about 40% of the one delivered to the conditioned space. Electricity is only due to the operation of three fans and two pumps. Cooling power can be controlled through variable speed fans. Fig. 1 shows the concept and the scheme of the system. A flow rate of outside air (1) is drown through one of the adsorption beds for its dehumidification and partial cooling. Thanks to the simultaneous moisture and heat exchange, dehumidification process can indeed be carried out at almost constant temperature (2). Afterwards, dehumidified air is mixed with the return air from the building which is at conditions (6), reaching the conditions of point (3). The mixed air, which has a flow rate equal to 140% of the air flow rate supplied to the building, enters the wet heat exchangers reaching the supply conditions at point (4).

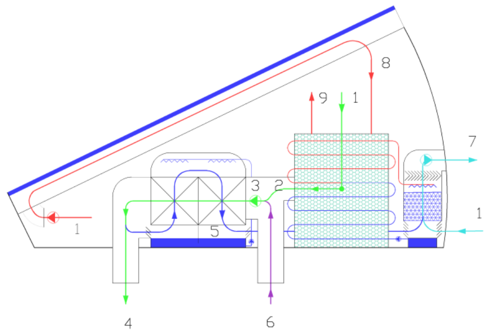


Figure 1: Functional scheme of the compact DEC.

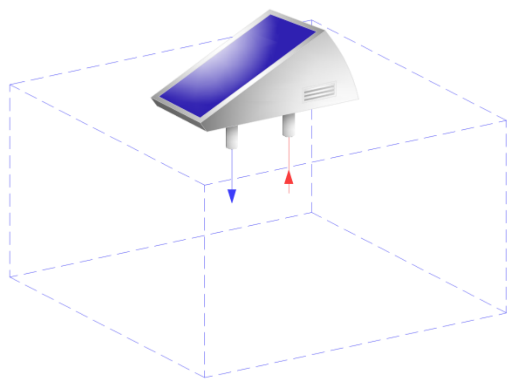


Figure 2: Possible installation of the compact DEC.

First tests aimed to the verification of the control and monitoring system and to the tuning of components started in June of 2013. After the this first phase, a the real monitoring was performed. Globally about 30 days of monitoring data are available with a total amount of 240 operation hours. With the aim to proof the proposed concept, a selection of one week operation data is presented here below [8].

The commutation between one bed to the other is obtained trough a special valve. At the beginning of the day, the system starts operating in adsorption mode the same bed used the day before. When the desired humidity ratio in the room cannot be reached, the control strategy commutes to the other bed remaining in this mode for a couple of hours when a new change in the beds operation mode occurs. Generally in the second half of the day, since less solar radiation is available, the commutation periods become smaller, but globally the humidity in the room can be controlled quite well.

Supply temperature ranges around 22.5°C until the hour when the pump of the wet heat exchanger starts to make cycles of switching on and off in order to control the temperature in the room. At that time, since the need of cooling becomes lower, cooling power is also reduced controlling the flow rate of the main fan. When the wet heat exchanger pump is on, temperature difference across the wet heat exchanger is about 5 °C. This value corresponds to an efficiency of the wet heat exchanger of about 45-48%. Such relatively low efficiency values are due to the fact that the flow rate mass ratio between secondary and primary side of the heat exchanger is only 0,28.

The outlet temperature of the solar collector ranges between 40°C and 60°C. Temperatures of the air coming out from the adsorption bed are slightly higher than of outside air ones, after the commutation between the beds occurs. It is worth to be noted that these values are considerably lower than the ones commonly registered in desiccant rotor based systems.

The EER values range from 5 to 10. The daily average value of the EER is 5,95 whereas the thermal COP is 1,21. For the examined test period about 38% of the delivered cooling power is related to the enthalpy difference in the adsorption bed, whereas the 62% is due to the wet heat exchanger contribution. The main part of electricity consumption is due to the main fan which is responsible for 62% of the total consumption.

As already mentioned, an important feature of the system is the possibility to store adsorption capacity in the beds which therefore can be used as latent storages. In order to show this behaviour, a test has been made switching on the system at 2:00 pm and stopping it at 10:00 pm. During the morning, solar heat was used to regenerate one desiccant bed, no other operation was carried out. As the system started, the bed which was working before in regeneration mode is now working in adsorption mode providing dehumidification with a humidity ratio difference between inlet and outlet of about 7 g/kg. As clearly shown by the humidity values registered at the outlet of the beds, the system could provide dehumidification for several hours after the sunset using only one bed. Since in DEC systems the cooling process depends on the dehumidification carried out, cooling of the building can be also guaranteed.

When the humidity set point value is not reached, the control strategy commutes from one bed to the other after the mentioned waiting time is gone. A certain swinging of the humidity at outlet of the adsorbing bed is expected because the other bed could not be regenerated during the morning so the two adsorption capacity are very different. It's also to be considered that, after 2:00 pm, the other bed could not be properly regenerated, since regeneration temperatures are low, in the range of 40 °C.

For the selected week, performance data are summarized in the following figures. In Fig. 3 the daily efficiency values of the solar collector are shown. As one can observe, the value are quite high ranging from 57% to 78%. Such high values are due to the fact the solar collector is working at low temperature, taking outside air at the inlet.

In Fig. 4 other energy performances indicators are reported. Daily EER values range between 3,3 and 6 with an average value of 4,8. The lower values of EER are especially due to the limited temperature difference between return and supply air. This is related also to the use of one heat exchanger instead of two in series.

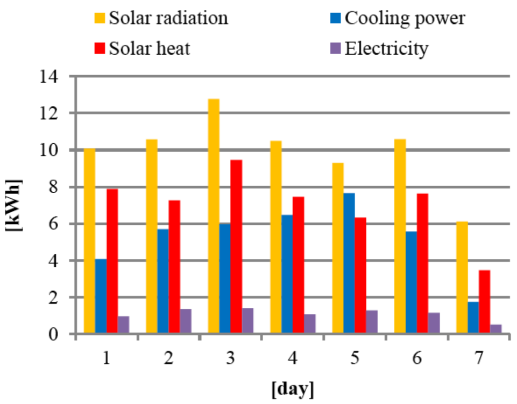


Figure 3: Main performance figures of the compact DEC.

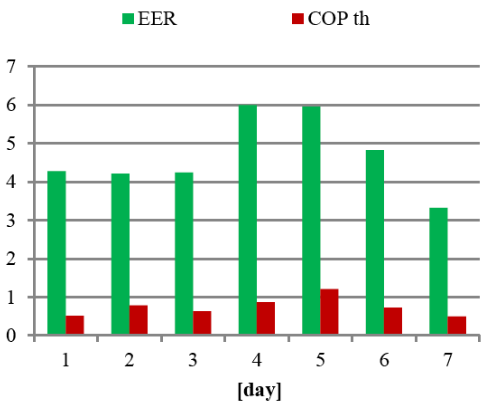


Figure 4: EER and thermal COP for cooling.

Results show the validity of the proposed solution and good performances both in terms of building temperature and humidity control. EER and thermal COP values are also encouraging, but optimizations are still possible. Cooling power delivered to the building could be easily increased by the use of two wet heat exchangers connected in series instead of only one. Electricity consumptions could be further reduced by a redesign of the air channels and fan sizing optimisation.

In relation to the desiccant beds, the opportunity to provide dehumidification and cooling also several hours after the sunset and to control the dehumidification process acting on the temperature of the bed have been shown.

Furthermore, the fact that adsorption and desorption processes happen in different times can be considered an advantage for the control of the dehumidification process. Further works will be carried out on the concept in order to increase the global energy performances.

3 ENERGY AND ENVIRONMENTAL PERFORMANCES OF SMALL SOLAR DRIVEN CHILLERS

The life cycle assessment (LCA) methodology was applied to assess resource use and other environmental burdens related to the all the life-cycle phases of another family of solar cooling systems. The investigated systems work with an absorption chiller assisted by a solar plant.

The benefits in terms of primary energy savings and greenhouse gases emission reduction were demonstrated by comparing the use of this innovative plant in substitution of a conventional one.

Energy and CO_2eq emission payback times and the energy return ratio of the system were calculated. The main components of investigated SHC plants are the following:

- absorption chiller, SolarNext/Pink chilli_PSC12 (12 kW), filled with ammonia/water solution;
- evacuated tube solar collector field (35 m^2 absorber area);
- hot water insulated storage tank (2000 l);
- wet cooling tower (32 kW);
- heating system for winter operation (gas boiler 20 kW);
- back-up system in summer operations (the same gas boiler used in the winter operation or a conventional cooling unit 10 kW);
- two-pipe fan coil units for cooling and heating distribution;
- three pumps.

Two different configurations of the plant were investigated (hot back-up and cold back-up) in two localities: Palermo (southern Italy) and Zurich (Switzerland) as depicted in Fig 5.

The first step of the analysis was on the use phase in order to calculate the energy consumed by the plant in two different localities (Palermo and Zurich). Simulations were carried out using TRNSYS with meteorological data from the METEONORM database.

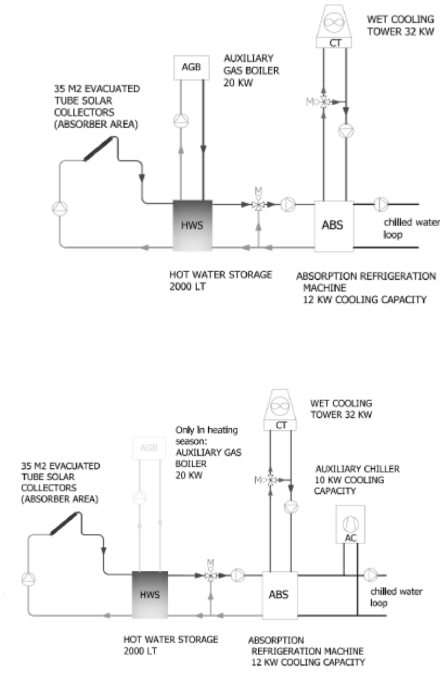


Figure 5: Functional scheme of the absorption plant with hot back-up (up) and with cold back-up (down).

The simulated load profiles are listed in Table 1. Monthly energy demands are shown in Fig. 6.

Table 1: Cooling and Heating loads from simulations and main building data.

	Building Inertia [kJ/K]	Peak Cooling Load [kW]	Peak Heating Load [kW]
Zurich (V= 1120 m^3, S/V=0,47 m^2/m^3)	174735	12,2	23,5
Palermo (V= 588 m^3, S/V=0,60 m^2/m^3)	94732	12,6	12,3

The energetic and environmental performances of the SHC plant were compared with those of a conventional plant, which consisted of a vapour compression chiller (10 kW; COP 2.5) for cooling and a gas boiler (20 kW) for heating during winter.

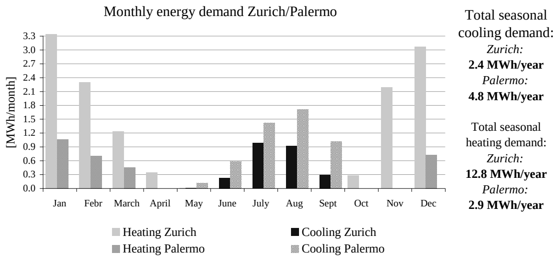


Figure 6: Monthly and seasonal heating/cooling demands Zurich and Palermo.

The hot back-up configuration with an absorption cooling machine and an auxiliary heater in Zurich reached PE savings of only 28%. The delivered cooling energy in the summer months in Zurich was very low (only 18% of heating energy delivered in winter); therefore, the machine was not optimally exploited. This indicates that components with notable electrical consumption are switched on for many hours with low efficiency in terms of delivered cooling energy. This decreased the electrical COP of the whole plant. Using an auxiliary chiller as back-up, the PE-saving in Zurich rose to 33%, although the values of the electrical and thermal COP decreased.

At the same time, the operating hours of the absorption machine with low efficiency were reduced and replaced by the auxiliary chiller with an average COP of 2.5. Results of energy production and consumption are non-linear due to restrictions in the simulations of control strategies with step-wise changes (e.g., electricity consumption for the external heat-exchanger).

The results for the absorption plant in Palermo were different; the absorption machine, either with hot or cold back-up, was more energy-efficient than the conventional plant. The configuration with hot back-up was more convenient (46% of PE saved) than the one with cold back-up (42% of PE saved). In this case, the climatic conditions favour a high solar heat contribution correlated with high cooling demand. Due to the more optimal exploitation of the absorption machine, the electrical COP was relatively high (5.0), as shown in Fig. 7.

Given that solar collectors are designed for the cooling operation, in winter, this solar plant is not sufficient to meet high heating loads. PE-savings in heating operation in Zurich were very low (34%), such as that seen in the solar fraction. In contrast, in Palermo, the same solar plant was suitable during the heating period, and a high PE-savings was obtained (84%).

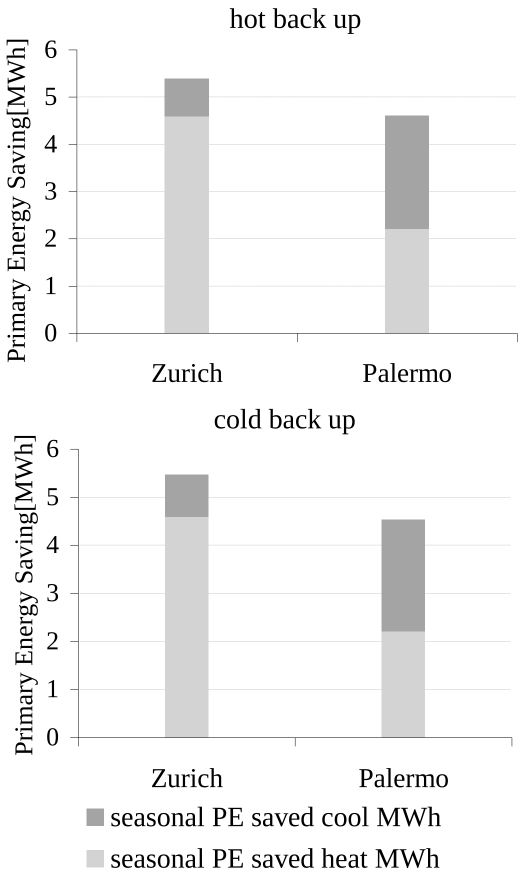


Figure 7: Total PE-saving in the hot back-up/cold back-up configurations (MWh).

It is interesting to consider the total PE-saving within one year of operation. Differences between hot and cold back-up on the total PE-savings were not detectable.

The heating season in Zurich had the highest influence on the total PE-savings. The results show that the advantages due to the use of RET depend on the climatic conditions of the installation site. In fact, even if the use of a SHC plant in substitution of a conventional one is more efficient in Palermo, the total PE-saving (for cooling and heating) is higher in Zurich, due to the higher energy demand for heating in that context.

The energy and environmental indexes selected to show the performances over the entire life of the investigated system (FU) are the following:

- Global Energy Requirement (GER), which represents the entire demand, valued as PE, that arises in connection with every life-cycle step of an economic good (product or service). The index is expressed in terms of MJ/FU of PE.
- Non-Renewable Energy (NRE), which indicates the rate of GER related to the use of non-renewable energy sources. It is expressed in terms of MJ/FU of PE.
- 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/ FU and is referred to a period of 100 year. The results are shown in Table 2 referring to the three considered phases: production, use, end-of-life.

Table 2: LCA performance of the investigated systems.

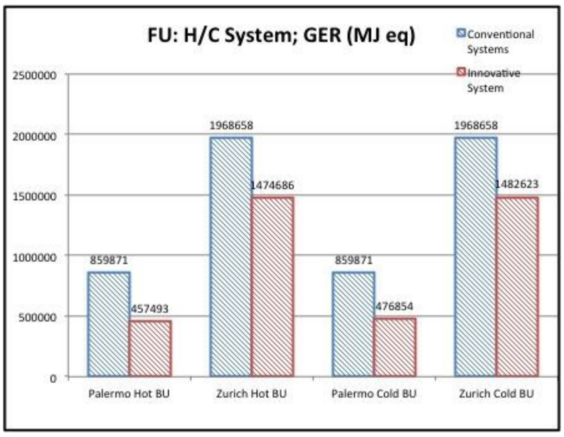
Palermo			
	NRE (MJ)	**GER (MJ)**	**GWP ($kgCO_{2eq}$)**
Production phase	117520	129505	9271
Use phase	321917	346860	20779
End of life phase	464	489	477
Total	439900	476854	30527

Zurich			
	NRE (MJ)	**GER (MJ)**	**GWP ($kgCO_{2eq}$)**
Production phase	119559	131605	9374
Use phase	1317125	1350068	69476
End of life phase	923	950	516
Total	1437607	1482623	79366

A detailed analysis of the production phase shows that the main contribution to GER and GWP was the production of both solar collectors (45–50% for GER and 37–50% for GWP) and the production of absorption chiller (21–24% for GER and 19–25% for GWP) (see Table 3).

Table 3: Energy and environmental impacts during the production phase.

Production phase	**GER (MJ)**	**GWP ($kgCO_{2eq}$)**
Absorption chiller	28058	1757
Solar collectors	59415	3437
Heat storage	15209	852
Cooling tower/heat rejection	2972	154
Gas boiler	1853	103
Glycol (only for plant in Zurich)	2100	103
Piping + insulation	8399	510
Pumps	1095	66
Conventional chiller (only for cold back-up)	12504	2394



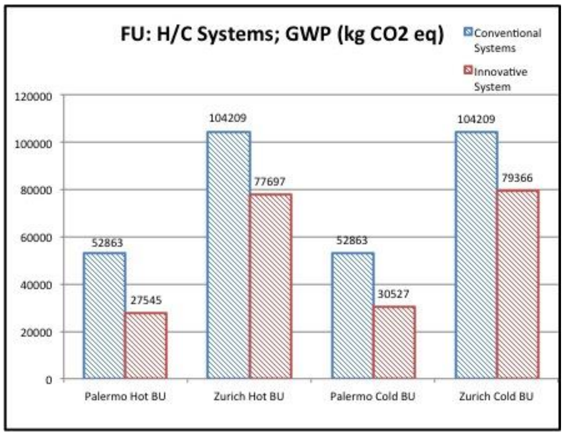


Figure 6: GER and GWP of innovative and conventional systems

A comparison of the GER and the GWP of the innovative system (hot or cold back-up) with those of the conventional system is shown in Fig. 6.

The comparison shows that the innovative system was better than the conventional system in terms of energy and environmental performances.
Starting from the LCA results of the SHC and conventional systems, the EPT, EMPT; CO_2eq and ERR indexes were calculated (Table 4).

The values of the payback indexes were almost fair. EPT ranged from 4.4 to 5.8 years, EMPT; CO_2eq ranged from 3.9 to 6.0 years, and ERR ranged from 3.8 to 5.0, in all cases. In general, the colder the climate, the lower EPT and EMPT; CO_2eq index and the higher the ERR index. For all the payback indexes, the hot back-up was slightly better than the cold back-up. The results of the payback indexes obtained show good performances for all the configurations from the energy and environmental point of view.

These results of the payback indexes quantify the net energy and environmental benefits related to SHC systems, despite the larger amount of energy and emissions related to their construction and end-of-life.

Table 4: LCA Payback indexes.

	E_{PT}(years)	$EM_{pt,CO2eq,}$ (years)	E_{RR}
Palermo hot back-up	5,1	4,0	4,3
Palermo cold back-up	5,8	6,0	3,8
Zurich hot back-up	4,4	3,9	5,0
Zurich cold back-up	4,8	5,6	4,6

4 CONCLUSIONS

In this work, an innovative compact desiccant cooling system for small scale applications is presented. The core component is a new desiccant bed consisting in a ordinary finned and tube air-water heat exchanger with air gaps between the fins filled with silica-gel grains. This component allows simultaneous mass and heat transfer, permitting to dehumidify and cool the processed air. In addition, the proposed solution permits also to regenerate the desiccant material operating at low temperature (max 60°C) using a standard solar flat plate air collector.

In order to test the proposed concept, a prototype was developed and monitored. Results show the validity of the proposed solution and good performances both in terms of building temperature and humidity control. EER and thermal COP values are also encouraging, but optimizations are still possible. Cooling power delivered to the building could be easily increased by the use of two wet heat exchangers connected in series instead of only one. Electricity consumptions could be further reduced by a redesign of the air channels.

In relation to the desiccant beds, the opportunity to provide dehumidification and cooling also several hours after the sunset and to control the dehumidification process acting on the temperature of the bed have been shown. Furthermore, the fact that adsorption and desorption processes happen in different times can be considered an advantage for the control of the dehumidification process.
Further works will be carried out on the concept in order to increase the global energy performances.

The analysis stressed that:
- LCA of renewable energy technologies (RET) has to include a detailed analysis of the use phase to assess the benefits that arise from the energy produced by the system during its useful life and to obtain reliable and high-quality LCA results.
- The use phase is responsible of the most part of energetic and environmental impacts of the plant life cycle.

- The innovative plant has a lower environmental impact than the conventional plant.
- The advantages of renewable energy technologies strongly depend on the climate of the installation site.

In particular, the total PE consumed during the use phase was 70–90%. The remaining percentage was mainly used for the production of the components of the plant; the consumption of the end-of-life phase was negligible. A detailed analysis of the production phase showed that the main PE consumption was related to the production of the solar collectors and the absorption chiller.

Analogous considerations can be made for the GWP. The performance of the system was compared to performance of a conventional plant with a vapour compression chiller and a gas boiler. The innovative plant had a lower environmental impact than the conventional plant.

To assess the effective energy and environmental advantages related to the use of innovative systems, energy and environmental payback indexes (EPT, $EM_{PT,\ CO2eq}$, ERR) were calculated from the LCA results. The results obtained showed good energy and environmental performance in all configurations. Moreover, the results indicated that the LCA of RET should include a detailed analysis of the use phase. This allows for proper assessment of the real benefits from the energy produced by the system during its useful life, despite the larger amount of energy and emissions related to RET construction. The advantages due to the use of RETs depend on the climatic conditions of the installation site.

5 ACKNOWLEDGEMENTS

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