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Energy balance and life cycle assessment of small size residential solar heating and cooling systems equipped with adsorption chillers

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ABSTRACT

Solar heating and cooling systems for space heating and cooling are experiencing a growing trend and interest. However, the actual energy and environmental performance of small/medium size installations is not clearly foreseeable. In this paper, an analysis of such systems using adsorption chillers in different European climates is presented. Solar systems have been simulated in TRNSYS and compared to a conventional system employing a vapour compression unit. The results have been used for a Life Cycle Assessment (LCA) study, determining the potential impact during the whole life of the system, from raw materials supply to its end-of-life. The LCA has been carried out by using the LCA tool developed in the framework of the International Energy Agency SHC Task 48. Results showed that the useful life of the system is a key parameter: for a useful life of 10 years, the conventional system performs better than the renewable-based one for almost all the locations. However, if a longer life is achieved (15 or 20 years), solar systems show environmental advantage under almost all the climatic conditions: the environmental benefits of using a solar system during the operation step counterbalance the additional impact generated during the other life-cycle steps.

1. Introduction

Facing the climate change and energy supply problems and assessing solutions to mitigate such issues have become topics of primary importance worldwide, affecting all sectors. The Energy Union strategies are built on the ambition to achieve a fundamental decarbonization of the energy system (European Commission, 2015a) in a cost-effective manner. This will be accomplished by moving to smarter, more flexible, more decentralized, more integrated, more sustainable, secure and competitive ways of delivering energy to consumers (European Commission, 2015b).

Buildings represent about 40% of European final energy demand and they consume more energy than any other sector of the European economy. Residential buildings consume around two third of the total energy of European buildings, and non-residential buildings consume one third (European Commission, 2017). Space heating and cooling has a significant impact on the energy consumption of buildings, up to 75% of the total energy demand (Ürge-Vorsatz et al., 2015). Moreover, the trend for energy demand is growing annually and, since much of energy used comes from fossil fuels, greenhouse gas (GHG) emissions are increasing as well (Allouhi et al., 2015a).

In such a context, renewable heating and cooling technologies play a vital role among the available options in a sustainable energy system since they allow the reduction of the use of primary energy from fossil fuels needed for heating and cooling applications (Anand et al., 2015) and, consequently, the reduction of GHG emissions. This has been identified by the European Commission as "no-regret" option in its Energy Roadmap 2050 as it can provide "locally produced" energy (Ivancic et al., 2014). Among renewable heating and cooling technologies, solar thermal cooling systems have already proven to be a viable and effective alternative. An overview of the technologies employed and their key features is given in (Wang and Ge, 2016), while in (Allouhi et al., 2015b) an economic analysis and the market trends for such systems are reported. What has been generally found is that the actual energy/economic savings linked to the installation and use of solar heating and cooling (SHC) systems are strongly affected by several boundary conditions: heating/cooling demand, installation costs in the chosen location, public incentives, price of energy (Eicker et al., 2015; Hartmann et al., 2011). The technical feasibility of SHC or poly-generation technology has already been proved, together with the effective

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Nomenclature

A	aperture area of solar collectors, m^2
E	energy, MWh
E_{year}	net yearly primary energy saving due to the operation of the SHC system, MJ
$E_{Overall}$	net primary energy saving during the overall lifetime of system, MJ
G	incident radiation, W/m^2
$GER_{SHC\text{-}System}$	primary energy consumed during the life cycle of the SHC system except for the operation phase, MJ
$GER_{Conv\text{-}System}$	primary energy consumed during life cycle of the conventional system except for the operation phase, MJ
GWP_{year}	net yearly avoided GWP due to the operation of the SHC system, kg CO_{2eq}
$GWP_{SHC\text{-}System}$	GWP generated during the life cycle of the SHC system except for the operation phase, kg CO_{2eq}
$GWP_{Conv\text{-}System}$	GWP generated during the life cycle of the conventional system except for the operation phase, kg CO_{2eq}
$\dot{m}$	flow rate, kg/h
Q	power, kW
T_m	average temperature of solar collectors, °C
T_a	ambient temperature, °C
η	efficiency

Abbreviations

COP	coefficient of performance
CPC	compound parabolic collector
DHW	domestic hot water
EPT	energy payback time, y
ERR	energy return ratio
FU	functional unit
GER	global energy requirement, MJ
GHG	greenhouse gas
GWP	global warming potential, kg CO_{2eq}
GWP-PT	global warming potential payback time, y
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
OPE	operational primary energy consumption, MWh/y
OPES	operational primary energy savings, MWh/y
SF	solar fraction
SHC	solar heating and cooling

possibility of an economic return of the investment, especially in warmer climates and for greater sizes (Vasta et al., 2016).

Among solar cooling systems available, adsorption systems represent a promising choice, since they can be driven by low-grade heat (< 90 °C), thus eliminating the need for concentrating solar systems, and employ water as refrigerant, which reduces hazard, corrosion and maintenance issues (Allouhi et al., 2015a). The growing interest towards such a technology is also due to the market availability of units in small-to-medium sizes and "solar kits" already comprehensive of all the components needed for the installation of a SHC system (Allouhi et al., 2015b). This has led to an increase in the number of installations, especially in growing countries in South America or Eastern Asia (Ren21, 2015).

However, to perform a rigorous analysis and assess the effective benefits of SHC systems, a more complete perspective is needed, taking into account not only the operation of the system, but its whole life cycle. A well-established and standardised methodology to fulfil this task is the Life Cycle Assessment (LCA), that accounts the use of resources and the environmental burdens of goods and services following a life cycle approach.

In the scientific literature, different studies assessed the economic, technical and environmental performance of solar systems, also considering their life cycle. Some of them are summarized in the following.

Beccali et al. (2012, 2014) applied the LCA methodology to compare a SHC system equipped with an absorption chiller and a conventional system, also assisted by a photovoltaic (PV) plant (grid connected and stand-alone). The analysis was performed in three different locations: Palermo (southern Italy), Zurich (Switzerland) and Rio de Janeiro (Brasil). The results indicated that, in many cases, the conventional system with the PV grid connected plant performed best. The stand-alone PV assisted systems performed worse than the PV grid connected and the solar system in nearly all the analysed cases, due to the high impact of the electricity storage life cycle. For all the examined locations the use phase is responsible of about 70–90% of the energy and environmental impacts of the plant life cycle.

Bukoski et al. (2014) applied the LCA to analyze the environmental impacts of implementing a solar/electric hybrid cooling system in a stadium of 15,000 seating capacity in Bangkok, Thailand. The life cycle emissions of the solar assisted absorption chiller system were compared to that of a conventional electricity-consuming vapour compression chilling system. The results showed that the net life cycle impacts of the solar system are reduced of about 26–40% when compared with those of the conventional one: the avoided impacts during the operation of the solar system outweigh the impacts caused during the remaining life cycle steps.

Finocchiaro et al. (2016) explored the performance of a compact desiccant evaporative cooling system, equipped with a photovoltaic/thermal plant, in comparison to standard conventional technologies. The production phase of the system showed a predominant role among the other life cycle steps, reaching a 95% share on the total for some environmental indicators, such as human toxicity. If a conventional system is compared with the solar system, it results that the former would report many indicators values higher by 200% in comparison to the latter.

Hang et al. (2014) developed a life cycle economic and environmental assessment of a solar cooling system with external compound parabolic concentrator solar collectors and an absorption chiller. A comparison of the solar system with a conventional one in two types of office buildings at three locations at California was performed. Two different solar cooling system configurations were considered: configuration 1 sizes the area of solar collectors and absorption chiller to meet the peak cooling demand, and uses natural gas as the only backup energy source; configuration 2 sizes the area of solar collectors and absorption chiller to meet half of the peak cooling demand, and uses natural gas as the backup energy source for the absorption chiller, while incorporates an electrical vapour compression chiller to meet the rest half of peak cooling demand. The results showed that configuration 2 can achieve lower present worth cost during the entire life cycle than the conventional systems, and even lower than the configuration 1. The solar system reduces 35–70% carbon footprint compared to the conventional systems, due to the free energy from the sunshine, and the configuration 2 achieves even lower carbon footprint compared to the configuration 1.

Jing et al. (2012) examined a solar building cooling heating and power system driven by solar energy and natural gas, installed in a commercial office building in Beijing, China. The integrated performance in the electricity loads and thermal loads operation strategy were compared. The results of the analysis indicated that the contributions of materials, operation and fuel stages are more important than the manufacture and transportation stages. In addition, the energy saving and pollutant emissions reduction of the thermal loads operation mode are better than that of the electricity loads mode.