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Solar cooling technologies. Design, application and performance of existing projects

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ABSTRACT

The present paper introduces the concept of solar cooling as a major issue in the valorization of the solar source in front of the challenge represented by the worldwide growing demand of cold. The most relevant solar cooling technologies are briefly discussed as well as their possible combination and implementation in different contexts. Some real-world installations are proposed as representative of possible plant design in a variety of climate and building integration conditions. Through these cases, trends of innovation are identified both for small and settlement scale applications, supporting the perspective of a more efficient exploitation of the solar cooling potential.

1. Introduction

The interest for solar cooling systems is on the rise, due to the concurrence of proceedings in solar driven technologies and dramatic growth in the demand for cooling services. As for other applications of renewable energies, after a long stand-by period, the number of studies and real applications is growing, even if the exploration of new approaches and their market exploitation might not seem fully systematic, yet. It is the typical complex arena of renewables, where the interaction among market-driven innovations, academic activity, and stimulating regulation are generating new ideas, then explorative projects and, possibly, a widespread adoption of the most effective solutions. For this reason, specific attention should be paid to real world solar cooling installations as they're the best showcases of the possible combination of existing and emerging technologies, where it is possible to gather consistent information about their performance and potential in terms of a larger adoption.

As a matter of fact, the idea of generating cold by the solar radiation is not new (Butti and Perlin, 1980). After about one century from the publication of the visionary textbook of Mouchot (1869), this concept has been further developed, among the others, by Harry Zvi Tabor in Israel (Tabor, 1962) and by the Italian pioneer Gino Bozza in the Solar Experimental Station of the Italian CNR in the '60 (Silvi, 2003).

The solar cooling concept, as most of the solar technologies, has been confined within the "curiosity-driven" domain until the first oil crisis in the early 70s of the XXth century. In the 80s many activities have been carried out, especially in the United States and Japan, and some remarkable results have been achieved in the introduction of new approaches and components, although with a limited number of market exploitation cases, due to economic constraints.

A new active drift started in the late 90s because of the growing evidence of the climate change, triggered by the use of fossil fuels, and the unsettled concerns about the safety of the nuclear options. The International Energy Agency, founded in 1974 as an autonomous body within the OECD, has established the Solar Heating and Cooling (SHC) Programme in 1977, as one of the first programs of action. Since the beginning, the solar cooling option has been considered a strategic perspective in the SHC activity and the SHC initiative has been well oriented in promoting real-world installations of solar cooling.

More recently, the European Union, within the implementation process of its decarbonization strategy (EU Commission, 2006), has issued the new building directive (EU Commission, 2010) which states that all new and refurbished buildings should be near zero energy by 2020. Together with the directive on the adoption of renewable sources (EU Commission, 2009), these policies are opening new opportunities for the broad application of solar cooling concepts in the warmer regions of Europe, where the cooling demand is already dominating in the building environment.

In spite of that, SHC still represents a tiny market even if it has been steadily growing in the last decade. Updated surveys performed by IEA-SHC (Jakob, 2015) are showing that the penetration of solar cooling systems in the market hasn't been so significant as

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Nomenclature

AC	air conditioning
VC	vapor compression
SC	solar cooling
SHC	solar heating and cooling
RAC	room air conditioner
GWP	greenhouse warming product
COP	coefficient of performance
CPC	compound parabolic collector
EER	energy efficiency ratio
ETC	evacuated tube collector
FPC	flat plate collector
PTC	parabolic trough collector
HTF	heat transfer medium
LFC	linear fresnel collector
PV	photovoltaic
BoP	balance of plant
ORC	organic Rankine cycle
DEC	desiccant evaporative cooling
CPV	concentrating photovoltaic
CPVT	concentrating photovoltaic and thermal
PBT	payback time

only about 1,200 installations have been recorded worldwide till 2014, most of those in Europe (Fig. 1).

Although, according to the last roadmap issued by the IEA-SHC working groups, solar cooling should represent at least 17% of the increasing cooling needs by 2050, the dominant technology for air-conditioning presently remains the electric vapor compression cycle. The number of VC based Room Air Conditioners (RAC) yearly sold units increased from about 44 million worldwide in 2002 to more than 94 million units in 2012. More than 100 million units were sold in 2014, and, under current trends, 700 million are expected by 2030 and 1.6 billion by 2050.

While in Europe, US, and Japan, AC market has been slowing down, in other countries, characterized by a fast growing population, AC sales are growing at 10–15% per year, following the earlier adoption of other house appliances, with still low penetration rates. Their demand will be triggered by the combination of climate change, population growth, access to better incomes, urbanization (Shah et al., 2015; Santamouris, 2016).

The growing request of cooling services is already affecting the electricity demand dramatically in many countries, turning into unsustainable seasonal peaks, an increase of cost of electricity and risks of brownouts (Balaras et al., 2007a, 2007b; Desideri et al., 2009a, 2009b).

As an example of such impact, Fig. 2 is clearly showing how the hourly electricity demand in Delhi is affected by the cooling demand in summer.

The impact of such trends on the amount of greenhouse gasses in the atmosphere will be dramatic, both due to emissions related to fossil electricity consumption and from the leakage of high GWP refrigerants. An improved efficiency of the VC units and the contextual adoption of a different class of refrigerants could mitigate this impact. Nevertheless, as a string solar radiation is available where the cooling services are highly desirable, a more radical action of contrast should come both from a diffused application of solar cooling systems (Kalogirou, 2004).

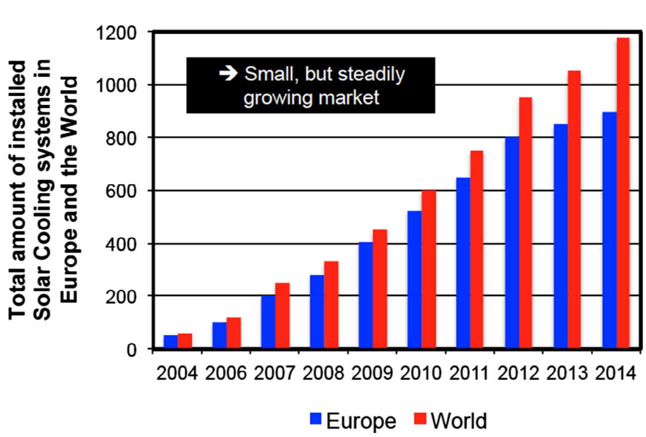

Fig. 1. Total amount of installed solar cooling systems in Europe and the world. Cited from Jakob (2015).

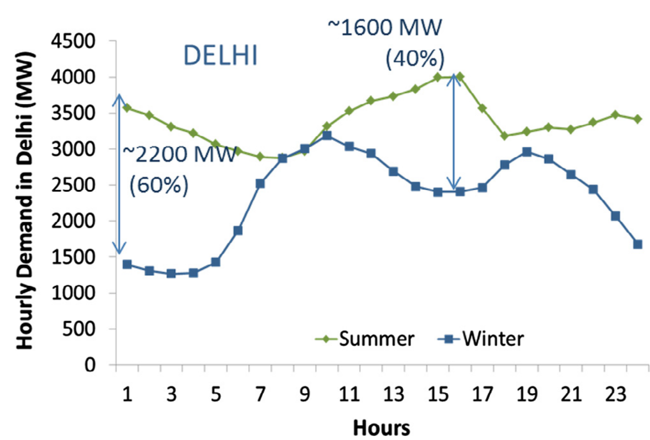

Fig. 2. Hourly electricity demand in Delhi: air conditioning load represents 40–60% of peak load. Source: Delhi State Load Dispatch Center (DSLDC), 2012. Cited from Shah et al. (2015).

This very strong market driver for the adoption of SHC systems is counterbalanced by two specific limiting factors: complexity and high investment costs. Most of the installations are either still linked to research or at the maturity of demo projects, and the payback time seems still too long, even in the presence of incentives. Thus, people goes for cheaper and simpler VC solutions.

Due to the improved cost/performance ratio, the combined installation of PV panels and conventional VC units is going to be considered a viable simple solar cooling option, especially by professionals. The alternative approach, consisting in solar thermal collectors combined with thermally driven chillers, is still much more investigated by the researchers, as the major technological breakthroughs have been expected there.

In the following paragraphs, general aspects of the solar cooling technology will be discussed and some significant pilot projects will be outlined, with the aim of identifying some of the key factors that could drive the full exploitation of the solar cooling potential.

2. Main characteristics of solar thermal cooling systems

The key components a solar cooling system are represented by (i) the solar collectors, (ii) a thermally driven chilling process, (iii) eventual heat rejection units to expel the waste heat of the cooling