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Comparison of photovoltaic and solar thermal cooling systems for office buildings in different climates

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Abstract

Photovoltaic systems combined with electrical compression chillers offer a high potential for energy efficient cooling with a high economic feasibility. Due to much higher energy efficiency ratios of electric chillers compared to sorption cooling systems, the heat rejection system is much smaller and thus auxiliary energy and water consumption lower than in sorption cooling systems. The overall system efficiency, auxiliary energy consumption and achievable solar fraction depend on the photovoltaic module technology, the compression chiller energy efficiency ratio and obviously on the temporal correspondence of solar cooling production and cooling demand. A systematic simulation study was carried out to evaluate the overall performance of photovoltaic compression cooling systems in office buildings for different climatic conditions worldwide. For each location and cooling demand the solar energy production for different surface areas was calculated and solar fractions, EER and auxiliary energy demand was determined. It could be shown that the primary energy savings for solar electric cooling and heating are comparable to solar thermal systems. As solar thermal systems include hot storage, they mostly provide higher solar fractions and in some cases higher primary energy savings. If electricity export to the grid or for appliance use is included in the primary energy analysis, photovoltaic cooling systems always have higher primary energy savings.

The total cooling costs for solar electric cooling are comparable to solar thermal cooling systems, if there is no feed in tariff for the excess PV electricity. If a grid export is possible and paid for, solar electric cooling systems are always more advantageous.

Keywords: Solar electrical cooling; Solar thermal cooling; Solar cooling simulation; Primary energy savings; Cooling costs

1. Introduction

Worldwide office buildings are increasingly air-conditioned. The conventional technology for air-conditioning are electric compression chillers with peak loads during the midday (Balaras et al., 2007; Desideri et al., 2009). To reduce the stress on the electrical networks and to save primary energy, thermally driven absorption chillers powered by solar energy or waste heat can be used (Eicker, 2014; ASHRAE, 1972). Also photovoltaic panels can power the chillers and provide peak electricity especially during midday high load conditions.

A range of authors did detailed studies of solar cooling systems in specific configurations and locations: Fong et al. (2010) compared five different types of solar electrical cooling and solar thermal cooling technologies in an office building in Hong Kong in TRNSYS. He showed that both types, solar thermal and solar electric cooling, have energy saving potentials between 8.0% and 43.7%. Solar thermal cooling and concentrating PV thermal cooling were investigated in combination with single effect absorption

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chillers in two locations in Italy (Buonomano et al., 2013). Primary energy savings with the evacuated tube systems were up to 74%, with the concentrating systems 100%, when compared to a reference electrical compression system. Bilgili (2011) analyzed solar electric-vapor compression refrigeration on type days (23rd of May, June, July, August and September) in the southern region of Turkey and found that the electricity produced by the solar system can cover the cooling energy demand in most cases. Also Otanicar et al. (2012) compared different technologies and showed that cooling load peaks are principally within the time of the maximum solar irradiation. Hartmann et al. (2011) demonstrated that with a large solar thermal collector area primary energy savings up to 40% (Freiburg) und 60% (Madrid) are possible. Here the solar electrical system performed better than the solar thermal system in terms of primary energy savings and economical terms.

A study of a hybrid system with an electrical chiller and a desiccant wheel in different climatic locations worldwide showed that this solar hybrid system is not yet economically viable (Wrobel et al., 2013). For being economically competitive initial costs for solar thermal collectors and absorption chillers have to be significantly reduced (Mateus and Oliveira, 2009). Most authors conclude, that only with investment cost decrease of significant public funding, solar cooling can be economically profitable (Calise et al., 2010).

As photovoltaic (PV) cooling has only become economically attractive during recent years due to the very strong PV investment cost reduction, there is very little systematic work available evaluating performance and costs. Also a systematic comparison between solar electric and solar thermal cooling for different climates in terms of economic and energetic performance is still missing and is done in the current paper.

2. Methodology

This study was carried out to systematically analyze the performance of photovoltaic powered compression chiller systems and compare them with results from solar thermal single effect absorption systems. For both systems a detailed analysis of the solar fractions, EERs, full load hours and the system efficiency are investigated for office buildings in various climatic, load and insulation conditions. The office building heating and cooling demand was obtained from dynamic building simulations using EnergyPlus. For each technology investigated, an energy optimized control strategy was developed which maximizes the primary energy efficiency. This control strategy was implemented in the modular simulation environment INSEL and system models were developed for a range of cooling systems. INSEL was used, as it has detailed validated models both for absorption chillers, solar thermal and photovoltaic modules, inverters and others and allows to program individual control strategies, which is extremely important in order to minimize the auxiliary energy consumption. Also an economic analysis was performed based on an annual full cost accounting and compared with the results of a reference system and the primary energy was analyzed.

2.1. Building load scenarios

To compare solar cooling system performance, office buildings were chosen as a relevant typology, as they are air-conditioned in most climatic zones worldwide. As building geometry and compactness has a significant impact on the energy demand, special attention has to be paid to define and classify it. Here a cellular side-lit building was chosen to represent the most typical office building built form (Brown et al., 2000; Steadman et al., 2000a,b). The office building was considered as one thermal zone. The three storey building has a total floor area of 5,040 m^2 and the net air volume is 12,500 m^3.

For each climate three different building load scenarios were considered and simulated: Case A with high internal loads for a well-insulated building, Case B with low internal loads for a well-insulated building and Case C with average internal loads in a poorly insulated building. As the internal loads are extremely important for the cooling load calculation, detailed schedules for each load type were defined with a distinction between weekdays with the main building use from 8 am to 5 pm, reduced use on Saturdays and no use on Sundays. The details of the building envelope and internal loads scenarios are described in Table 1.

The cooling and heating energy demand of such a middle size office building was dynamically simulated in six different climatic conditions using the EnergyPlus software (Riyadh, Jakarta, Madrid, Barcelona, Stuttgart and Cologne). Global horizontal irradiance and ambient temperature data in hourly resolutions were taken from the

Table 1
Building envelope specifications and maximum internal loads of each scenario.

Case	Façade		Roof		Window		Solar protection	Internal loads		
	Insulation (cm)	*U*-value (W/m^2K)	Insulation (cm)	*U*-value (W/m^2K)	*U*-value (W/m^2K)	*g*-value (%)	*b*-value (%)	Lighting (W/m^2)	Equipment (W/m^2)	People (W/m^2)
A	14	0.319	20	0.235	1.1	60	40	18	15	8
B	14	0.319	20	0.235	1.1	60	40	9	5	5
C	5	1.365	5	1.544	2.6	80	40	13	10	7