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A universal method for performance evaluation of solar photovoltaic air-conditioner

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ABSTRACT

Photovoltaic air-conditioner (PVAC) exhibits the advantages of high energy efficiency and convenient building integration, among solar cooling and heating technologies. The objective of this study is to propose a universal and straightforward method for performance evaluation of PVAC. Sixteen scenarios are simulated by TRNSYS to compare the performance of PVAC in different climates and building types defined by the Chinese national standards. Indicators such as solar fraction (*SF*), self-consumption ratio (*SCR*), solar *COP*, and return of investment (*ROI*) are used for evaluating energy and economic performances. The results demonstrate that the performance of PVAC is significantly affected by climatic conditions and building types, and thus, the feasibility of PVAC can be conveniently estimated based on the data provided by the Chinese national standards. A PVAC exhibits higher *SF* and *SCR* in areas subjected to high temperatures during summer and in office buildings, business malls, and hospital buildings, which mainly operate in the daytime. The building types in the order of decreasing *ROI* are business mall, hospital buildings, hotel, and office buildings. A comprehensive evaluation indicator is proposed to optimize the PV capacity and is useful to evaluate both the energy and economic performances of PVAC.

1. Introduction

The use of fossil fuel has raised significant concerns worldwide. Reports (World Energy Council, 2016; International Energy Outlook, 2016.) revealed that fossil fuels, including coal, oil, and natural gas, continue to account for approximately 85% of the present primary energy consumption, while the energy consumed by the buildings sector accounts for 20.1% of the total delivered-energy consumed worldwide. To reduce the consumption of fossil fuels in the building sector, interest in solar cooling has been increasing dramatically.

The concept of solar cooling arose from the assumption that solar energy could adequately match the building cooling demand in hot summer, when the solar radiation and ambient temperature attain their peaks during the year. The coincidence of solar power and cooling load could significantly contribute toward reducing the high electricity demand of utility grids and confronting the challenge of global warming. For the moment, solar cooling mainly consists of solar photovoltaic (PV) driven vapor compression cooling (Li et al., 2015; Bilgili, 2011), solar mechanical compression cooling (Zeyghami et al., 2015; Abdulateef et al., 2009), solar absorption cooling (Zhai et al., 2011), solar adsorption cooling (Wang and Oliveira, 2006), and solar desiccant cooling (Dai et al., 2002). Among these, solar electric compression cooling is powered by solar PV and can be categorized into grid-connected and off-grid systems. Since PV systems could be also used to power heat pumps (reverse cycle of electric compression cooling) for space heating. The term photovoltaic air-conditioner (PVAC) is more appropriate to describe the integrated system. The others use solar thermal energy and are usually equipped with various types of solar thermal collectors such as flat-plate collectors and evacuated-tube collectors (Wang and Ge, 2016).

For grid-connected PVACs, both the PV system and the power grid can supply energy to the air-conditioner. The excess PV power can be fed into the grid so that the PV system could always operate under MPPT (maximum peak power tracking) function (Kouro et al., 2015). In terms of application, grid-connected PVACs are always regarded as a part of building energy systems. Relevant researches focus on control strategies which can smooth the PV generation (Mammoli et al., 2012), lower the economic cost (Schibuola et al., 2015), and improve the indoor thermal comfort (Zhang et al., 2013). Off-grids PVACs are always equipped with an energy storage system either in form of electrical

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energy storage (Li et al., 2015) or thermal energy storage (Xu et al., 2018). The energy storage system is charged when the PV generation is surplus, and is discharged when the solar radiation is low. Wang et al. (2015) compared the energy saving performance of battery storage and cold storage for off-grid PVAC systems, and found that the energy saving potential of the cold storage system is worse than the battery system since the COP (coefficient of performance) is relatively low for cold storage air-conditioners. However, off-grid PVACs with battery are still economically infeasible at the moment.

Solar energy production and building cooling demand are highly sensitive to local climate. Related researches are aimed at comparing the performances of various types of solar cooling technologies in different areas. Fong et al. (2010) investigated the aforementioned five types of solar cooling in an office building in Hong Kong. The simulation platform TRNSYS (Klein et al., 2011) was used, and the comparison of key indicators such as solar fraction, coefficient of performance, solar thermal gain, and primary energy consumption was conducted. It was observed that solar electric vapor compression refrigeration and solar absorption refrigeration exhibited the highest energy conserving potential in subtropical areas such as Hong Kong. Eicker et al. (2015) carried out a simulation study to evaluate the overall performance of photovoltaic vapor compression cooling systems and solar thermal absorption cooling systems in office buildings for six climatic conditions worldwide. Results demonstrated that the primary energy savings for solar electric cooling and heating are comparable to those of solar thermal systems. However, the feed-in tariff of excess PV electricity, which could make solar electric cooling more advantageous, was not analyzed in detail in the study. Hartmann et al. (2011) conducted a similar analysis in which the solar thermal and photovoltaic options in an office building for two European climates were investigated. The superiority of PV cooling was also revealed. Mokhtar et al. (2010) conducted a comprehensive techno-economic research of solar cooling, which included 25 feasible combinations of solar energy collection and cooling technologies. The analysis revealed the criticality of solar fraction and storage size in the design of solar cooling systems. Additionally, the omission of the relation between cooling demand and solar resource availability can result in overestimation of the potential of solar cooling.

Based on the previous literatures, it could be determined that among all the solar cooling types, photovoltaic vapor compression cooling exhibits high potential for building application in terms of economic and energy conservation aspects. Its highly efficient cooling system and convenient integration with conventional buildings are widely accepted. In addition, solar electric vapor compression heating, which exhibits a similar mechanism as solar electric vapor compression cooling, is also studied for use during winter, in the above literatures. Hence, photovoltaic air-conditioner (PVAC), the combination of PV electric cooling and heating, could be a preferable solution for buildings where heating and cooling are both required.

However, the following problems have not been adequately addressed in previous works. First, while local climate exerts a significant effect on PVAC performance, the climate factor was not systematically studied. For example, the coupling effect of ambient temperature and solar radiation on PVAC has not been carefully analyzed. Moreover, there is no method to evaluate the feasibility of PVAC according to conventional references such as national standards or codes. Second, the performance of PVAC depends on the climatic conditions as well as the building types; this has not been carefully studied. Based on their functions, buildings can be categorized into office building, business building (such as shopping mall), residential buildings, etc. The discrepancy of these buildings due to their energy consumption characteristics could exert very high effects on system performance. Third, the utility grid can serve as an infinitely large battery to store the excess PV energy from grid-connected PVAC. The optimal sizing of grid-connected PVAC is worth investigating; however, it is not adequately addressed in the previous studies. Therefore, in order to better facilitate the application of PVAC, an explicit and exclusive study of PVAC is urgently required.

The objective of this study is to propose a universal and straightforward method for performance evaluation of PVAC. The main purposes of this study are to (1) evaluate the performance of PVACs for typical climates and building types based on standards and codes, (2) optimize the PV capacity of PVAC by a newly proposed index. Specifically, sixteen scenarios are simulated by TRNSYS in the study to compare the performance of PVAC in different climates and building types defined by the Chinese national standards. The energy and economic features of PVAC in the scenarios are determined in the simulation results and practical recommendations for system design are inferred. A new index *CEI* is proposed for PV capacity optimization and a case study in Shanghai has been carried out. The results of this paper can help to assess the performance of a PVAC in advance with the knowledges of its local climate and building type.

2. Research method

2.1. System description

The grid-connected photovoltaic air-conditioner system is selected for investigation owing to its superiority toward the off-grid in terms of economic characteristic and system reliability (Li et al., 2017). The rationale of the grid-connected photovoltaic air-conditioner system is displayed in Fig. 1. Photovoltaic panels gain energy from sun light and generate electricity. The PV electricity is transmitted to the air-conditioner system, including the indoor and outdoor units, and interacts with electric grids. The air-conditioner in this study refers to the heat pump, which can provide cooling and heating to maintain a steady indoor room temperature. The relationships between the energy flows involved in a PVAC in summer can be presented as follows:

$$E_{PV} = E_{sun}\cdot\eta \quad (1)$$

$$E_{grid} = E_{PV} - E_{AC} \quad (2)$$

$$E_{cooling} = E_{AC}\cdot COP \quad (3)$$

$$E_{cooling} = E_{outdoor} + E_{indoor} \quad (4)$$

where E_{sun} (kWh) is the solar radiation on the plane of the PV arrays, E_{PV} (kWh) is the electricity produced by the PV, η *is* the energy conversion efficiency of the PV modules, E_{AC} (kWh) is the electricity consumed by the air-conditioner, and E_{grid} (kWh) is the electricity flow as a result of interaction with power grids. The value of E_{grid} can be either positive or negative depending on the difference between E_{PV} and E_{AC}. *COP* represents the coefficient of performance of the air-conditioner, while $E_{cooling}$ (kWh) denotes the cooling effect generated by the air-conditioner. $E_{outdoor}$ (kWh) is the heat transfer from the outdoor environment caused by heat convection and solar irradiation. E_{indoor} (kWh) denotes the heat generated by indoor factors such as human

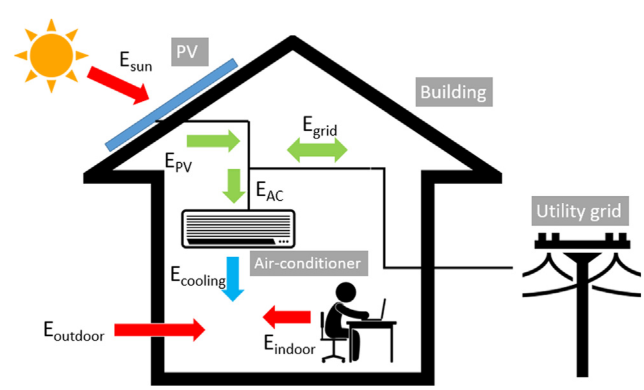

Fig. 1. Schematic diagram of photovoltaic air-conditioner system (summer).