Experimental and numerical studies to assess the energy performance of naturally ventilated PV façade systems

Mehdi Shahrestani \textsuperscript{a}, Runming Yao \textsuperscript{a,\ast}, Emmanuel Essah \textsuperscript{a}, Li Shao \textsuperscript{a}, Armando C. Oliveira \textsuperscript{b}, Arif Hepbasli \textsuperscript{c}, Emrah Biyik \textsuperscript{c}, Teodosio del Caño \textsuperscript{d}, Elena Rico \textsuperscript{d}, Juan Luis Lechón \textsuperscript{d}

\textsuperscript{a} School of the Built Environment, University of Reading, Whiteknights, PO Box 219, Reading RG6 6AW, United Kingdom
\textsuperscript{b} Centre for Renewable Energy Research, Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal
\textsuperscript{c} Department of Energy Systems Engineering, Faculty of Engineering, Yasar University, 35100 Bornova, Izmir, Turkey
\textsuperscript{d} Onyx Solar, C/ Rio Cea 1-46, 05004 Ávila, Spain

\textbf{Abstract}

This paper presents a holistic approach to assess the energy performance of a naturally ventilated PV façade system. A rigorous combined experimental and numerical approach is established. The real energy performance of the system has been evaluated through a long-term high resolution monitoring of a typical ventilated PV façade system. A numerical model based on TRAinsient SYstem Simulation (TRNSYS) package was developed to assess the thermal and energy performance of the system, which has been verified by a series of statistical analysis using the data collected from the experiment. The validated model was then used to assess the energy and thermal performance of a 7.4 kWp prototype ventilated PV façade system in Izmir, Turkey. The results of this study demonstrated that ventilation in the air cavity of the PV façade system could significantly improve energy performance of the system even in a southeast facing façades. The quantitative analysis provides useful guidance to the system designers for the improvement of energy efficiency of the PV façade system.

\textcopyright 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

\textbf{1. Introduction}

According to the international Kyoto protocol (1997), the UK government is committed to reduce greenhouse gas emissions by 30\% and 80\% below the 1990 level respectively by 2020 and 2050 (DECC, 2008). Utilising renewable technologies in buildings plays a significant role to achieve this commitment in the UK building sector. Based on the 2020 vision provided by the UK photovoltaic manufacturers association, utilising PV systems only on south-facing roofs and façades has the potential of generating 140 TWh/year electricity, which is almost 35\% of electricity consumption in the UK (UKPV, 2009).

The first Building Integrated Photovoltaic (BIPV) system was installed in 1991 in Aachen, Germany (Benemann et al., 2001). At the beginning, the scale of installation of BIPV systems was around 5–10 kWp. However, the installation of a 1 MWp system at the Academy Mont-Cenis Herne was the beginning of an increasing demand for this system. Ventilated PV façade systems are one of the main arrangements of the BIPV systems that have been studied over the last two decades. One of the early studies in this field was conducted by Balocco (2002) in order to develop a simple model to assess the energy performance of the ventilated façade systems. Despite the huge success of the developed model in broadening the understanding of the energy performance of the ventilated PV façade systems; it was a steady-state model that assumed the velocity of the air within the air cavity based on the air temperature only. In addition, the outcomes of verification of the model with experiment were reported for just one representative day. In another study, Omer et al. (2003) assessed the actual performance of BIPV systems and compared the actual and predicted energy performance of two BIPV systems over a twelve-month period. The results of this study demonstrated a significant difference between the outcomes of PVSYST (a simulation tool) and experiment. This was mainly due to the effect of microclimate conditions on the energy performance of the system.

In an attempt to improve the accuracy of the numerical models in estimation of the energy performance of BIPV systems, Mei et al. (2003) developed a thermal model based on TRNSYS. This study addressed the dynamics thermal behaviour of the BIPV systems. However, it was only able to consider the effect of force ventilation within the air cavity of ventilated PV façade systems. In addition, the outcome of validation was only reported for a few representative days.
In another study, Infield et al. (2006) developed a simplified model to predict the thermal performance of the BIPV systems using steady-state analysis. Despite the simplicity of the model in analysing the thermal performance of BIPV systems, the force convective heat transfer within the air cavity was modelled empirically using the data collected from an experiment. This was one of the resultant limitations of the adopted approach in this simplified model, which made the model not suitable for naturally ventilated PV façade systems. In addition, the simplified model has not been validated with the experiment results.

Taking into account the effect of natural ventilation on the BIPV systems, Fossa et al. (2008) studied the thermal behaviours of the system in laboratory conditions. The results of experiment were compared with a numerical study, which revealed a very close correlation between the thermal behaviour of the system in both the experiment and the numerical model. However, in the experiment, a set of electrical resistances was used instead of PV modules, which could not be able to represent the thermal performance of PV modules especially under different irradiation levels. In another study, the natural convection in PV integrated double skin façade system was studied by Lau et al. (2011). However, the influence of natural ventilation was only reflected on the thermal behaviour of the system not the energy performance of the PV modules.

Han et al. (2013) evaluated the performance of ventilated double skin PV façades and compared the thermal performance of such a system with double skin façades. They developed a steady-state finite difference model and compared the simulation results with the outcome of a small-scale experiment. The results of this study demonstrated that ventilation in the PV façade reduced the possibility of potential overheating in hot weather conditions. However, the electrical performance of the PV façade has not been addressed and the validation of the model has been conducted for a steady state condition without reflecting on the thermal and energy performance of the system under dynamic and ever-changing weather conditions.

Gaillard et al. (2014) conducted an experimental study to assess the thermal and electrical performance of a naturally ventilated PV façade system. Airflow rate, irradiation and the system-generated power together with the amount of heat gained throughout the cavity of the PV façade system were provided in some typical days in each season. However, due to the pleated arrangement of the PV façade, the studied prototype ventilated PV façade could hardly represent the typical ventilated PV Façade systems. In addition, the holistic energy performance of the system including the annual electricity generation has not been addressed.

One of the most recent studies in this field has been carried out by Peng et al. (2016). They investigated the energy performance of the double skin PV façade system using both experiment and simulation. The simulation model was developed using EnergyPlus software and validated by experimental study between October and February. Despite, providing a holistic energy performance of the ventilated PV façade system, the developed model was validated only against the electricity generation and temperature of the PV modules respectively over 5 months and 1 week. In addition, a very significant influence of irradiation level on the efficiency of the PV modules (Skoplaki and Palyvos, 2009) has not been addressed.

From the literature review, it is evident that there have been a few studies that addressed the holistic energy performance of naturally ventilated PV façade systems to some extent. In addition, the developed numerical models to simulate the thermal and electrical performance of the ventilated PV façade systems were mainly focused on force ventilation regimes and were validated using experimental data collected over a limited period, which could not represent the varying operative conditions of the system. The aim of this research is to provide the holistic assessment of energy performance of a typical ventilated PV façade system through a rigorous numerical and experimental study. The outcomes of the experiment conducted over a period of ten months are used to verify the numerical model that is developed to assess the energy performance of the system. The verification of the model is conducted considering the energy performance of the system together with the most challenging parameters associated with ventilated PV façade systems including the PV surface temperature and airflow rate passing through the cavity of system.

2. Research design

This study is designed in three main parts. In the first part, an experiment is set-up to assess the performance of a typical ventilated PV façade system in real conditions. The details of experiments are provided in Section 3.

In the second stage, a numerical model is developed to predict the performance of the ventilated PV façade systems and the model is verified using the experiment results. The numerical model is developed based on TRNSYS simulation package. The numerical model and its associated verification process are described in Sections 4 and 5 respectively. However, prior to the development of the model, a number of simulation packages including TRNSYS, ESP-r, PVSYS and EnergyPlus (Klein et al., 2009; EnergyPlus, 2011) were reviewed. In the open literature, several investigations in this field have been conducted through different simulation packages. Crawley et al. (2005 and 2008) conducted a comprehensive comparison study for the existing simulation packages. It shows that TRNSYS is one of the most appropriate tools for the study of the solar energy systems. In addition, in terms of software validation, TRNSYS is one of the listed simulation programs in the Building Energy Software Tools Directory of the US Department of Energy (DoE) and International Energy Agency (IEA) (Neymark and Judkoff, 2004). Moreover, several successful studies have been conducted using this tool (Kalogirou, 2001; Mei et al., 2003). Hence, the latest release of the TRNSYS simulation package (Version 17) is selected to assess the energy performance of the BIPV system in this study.

The last part of this study is designed to implement the verified model to assess the energy performance of a 7.4 kWp ventilated PV façade system in a Mediterranean weather conditions, in Izmir, Turkey, which is described in Section 6.

3. Experiment design

The experiment is set up on the Whiteknights campus of the University of Reading in the UK, 51.4°N, 0.94°W. It includes six Crystalline Silicon (c-Si) modules in two rows and three columns, installed on a South facing wood wall adjacent to the experiment shed. Location and geometry of the experiment is provided in Figs. 1 and 2.

The 150 mm air cavity between the PV modules and the back wood surface of the PV façade is naturally ventilated and air is passing through from three main openings of the façade; two openings at the top and bottom of the cavity and one gap between the first and second rows of the PV modules (Fig. 2). The thermal and physical properties together with electrical and optical properties of the PV modules are provided in Tables 1 and 2 respectively.

To assess the electrical efficiency of the PV modules at conditions other than Standard Test Conditions (STC), two influential parameters are taken into account, which include the total irradiation level and PV module temperature.

The influence of PV module temperature on the electrical efficiency is considered using the following equation:

\[ \eta_T = \eta_{STC} \times (1 - \beta \times (T - T_{STC})) \]  

(1)