Demonstration of the PV ventilated façade feasibility as a distributed energy approach for MENA region countries

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Abstract: The expected relevant role, within the new energy paradigm of photovoltaic (PV) solar energy is mainly based on the rapid advances of research and development in the PV field. In this sense, the current state of the art of these innovative technologies has allowed reaching the integration of PV glass products in an attractive and efficient manner. This approach is known as Building Integrated Photovoltaic (BIPV) Solutions which insertion ensures an enormous future for the distributed energy approaches as an energy-efficient measurement for retrofitting applications as well as smart solar solutions for new buildings designed under sustainable criteria.

In this respect, Onyx Solar, as a partner of REELCOOP 7th Framework Programme Project (Research Cooperation in Renewable Energy Technologies for Electricity Generation) in collaboration with University of Porto, University of Reading and University of Izmir, has been involved in the implementation of scale-up methodology capable of predicting the electrical behaviour of these technologies under a BIPV approach in order to demonstrate its feasibility in countries of the Middle East and North Africa region (MENA). This mentioned methodology covers several key steps such as simulation analysis developed by TRNSYS model, as well as optimized designs and real installation of a ventilated façade in a demonstrative building located in Izmir, Turkey.

This paper is focused on summarizing present relevant results and conclusions from the initial optimized design stage to the scale-up phase associated to the real application of a PV ventilated façade based on crystalline silicon technology at the University of Izmir.

Key words: BIPV, MENA, REELCOOP, PV facade, scale-up

1 Introduction

The share of renewable energy for electricity generation is expected to increase to 40% in 2020, in order to meet the EU target of 20% overall energy consumption from renewables, and it may increase to 66% in 2030 and 100% in 2050, according to the European Renewable Energy Council (EREC). The technologies which will have the highest growing rate from 2020 to 2050 are photovoltaics and concentrated solar power.

The European Union’s SET-Plan [1] established as technological priorities up to 2020 to demonstrate the commercial readiness of large-scale photovoltaics (PV) and concentrated solar power (CSP), as well as the development of a European electricity grid able to integrate renewable and decentralised energy sources. This means that no single solution is expected to meet the demand of electricity consumption, with several electricity generation systems operating in parallel, both at micro and large-scales.

For all the renewable energy targets to be achieved at European and World level, a wide dissemination of the major technologies for renewable electricity generation is needed. This involves the participation of countries in regions with high renewable energy resources, such as the MENA region. Special attention should be given to increase the research and development capacity on these technologies in these regions.
regions.

In this sense, the overall aim of REELCOOP is to significantly enhance research cooperation and knowledge creation on renewable electricity generation, involving Mediterranean partner countries (MPC), while at the same time developing and testing new renewable electricity generation systems. The proposed systems are being developed by European organizations in collaboration with MPC partners, and tested under real-life operating conditions in the MENA region, thus establishing a cooperation network amongst partner countries.

Within this general approach, one of the project aims is the design and construction of a PV system integrated in a ventilated façade. To achieve this, the electrical and thermal performance of the both crystalline silicon (c-Si) and dye-sensitized solar cells (DSC) PV technologies has been experimentally assessed. By integration of test PV modules in a test site at the University of Reading, the performance of the ventilated façade system was assessed using both experimental and numerical simulation. After verification of the numerical model using experimental results, the developed model was reliably used in the design and arrangement of the ventilated façade prototype to be installed at Yasar University. Identifying the most promising façade for installation of the system, 24 different design solutions/scenarios have been investigated for PV modules. Finally, considering the electrical efficiency and the thermal characteristics of the system under each scenario, the most appropriate design solution has been proposed for installation of a 6 kWp PV ventilated façade system in Izmir, Turkey.

2 Small-scale prototype development, testing and validation

According to the aims mentioned, this section summarizes the research activities and remarkable in regards to the small-scale prototype developed at the University of Reading. First of all, 1600mm x 750mm double laminated crystalline 4mm/4mm tempered BIPV units were successfully fabricated by Onyx Solar and then installed and tested by the University of Reading as prototype of ventilated façade. The BIPV units showed 155 Wp power output under STC conditions and this performance was used as reference for further testing in Reading. A detailed monitoring system installation for electrical measuring and testing was designed and provided to the University of Reading based on micro-inverters to follow energy generation performance at different air cavity conditions. Six c-Si modules were installed and thermal and electrical performance of the system was experimentally studied. In addition, a numerical model was developed to assess both thermal and electrical performance of the ventilated façade system. The developed model for simulation of the performance of PV ventilated facades was verified by using the experimental results.

2.1 BIPV glass modules design and fabrication:

BIPV applications require some modifications in regards to architectural aspects that are mainly related to the final module assembly step. This modification allows working with the module in a similar way to a conventional architectural glass, which makes easier its integration with conventional structural systems. Better light transmission properties can be also obtained when using this configuration. In addition, the use of a glass-glass configuration leads to more stability from a mechanical point of view. Therefore, an aluminum frame can be discarded, also improving aesthetics.
Figure 1 shows a frameless glass-glass module with mono-crystalline silicon cells. The final transparency degree depends on the gap between cells and distance from cell to glass edge. According to these indications, the full fabrication process of the BIPV modules for the small-scale prototype mainly consisted of the following steps:

**Automatic cells welding and string development:** The cells were interconnected in strings under the automatic welding lines. This is a fully automatic process machine with the production conditions (vacuum, optimizing ribbon and flux, and fixing welding temperature). The process has its own automatic QA procedure by means of infrared and microscopic image detection and ohmic contact measurements. In this way, any defect observed in the welding process results in an automatic rejection of the given string. No cell breakage is allowed and the maximum deviation from ribbon to cell bus-bar is +/-1 mm.

**Manual string interconnection:** Due to the dimensions of the BIPV units, it is mandatory to carry out the interconnection between strings manually. In this sense, within the procedure the interconnected strings were electrically checked and the overall unit passed a new visual inspection paying attention to several aspects such as ribbon quality, string deviation and EVA foils quality. Any defect or deviation from drawings specifications results on a product rejection at this production step.

**Lamination:** Once the strings were interconnected, the double glazing was placed in the laminator. An L-shape steel profile was introduced as a framing in the glazing perimeter allowing perfect alignment and minimizing mechanical stress of the top glass over the perforated cells. The recipe of the lamination was customized for this project at 20 minutes at a maximum cycling temperature of 145 °C and $10^{-2}$ Torr of vacuum. Once the lamination process was finished and BIPV units were cooled off, a new visual inspection was carried out where aspects such as the perfect cell alignment or the absence of encapsulant burbles were checked. As in the previous step, any of the aforementioned defects were lead on the BIPV rejection.

**Final Junction Box interconnection and testing:** At this step, the JB was placed in the ribbon terminals and sealed by PV 804 DC silicone. Then, the verification procedures were carried out by means of visual inspections, final electrical testing, etc.
2.2 Design and simulation of the small-scale PV ventilated façade system

Based on the technical preliminary information of the PV modules, the performance of the ventilated façade was firstly simulated under different arrangement scenarios. This numerical analysis aimed to find the most appropriate arrangement of the mentioned modules for the experimental study at the University of Reading. The size of the air cavity between the PV modules and the back surface of the ventilated façades is another parameter considered in this case study. Therefore, two practical gap sizes, 150 and 250 mm, were further studied.

The outcomes of simulation demonstrate that increasing the air cavity depth from 150 to 250 mm contributes to an annual average of 1.6 to 3.5% drop in the velocity of the air passing through the cavity. This drop on the air velocity is reflected in both surface temperature of the PV panels and temperature of the air leaving the top opening of the cavity. The surface temperature of PV panels rises up to 2.2 °C when the depth of the air cavity is increased from 150 to 250 mm. In addition, this air cavity enlargement has influence on the temperature of the air leaving the cavity at the top of the façade. By increasing the depth of air cavity from 150 to 250 mm, the temperature of the air leaving the gap is reduced by up to 2.9 °C. By increasing the depth of the air cavity, the velocity of the air passing through is reduced, which results in lower convection heat transfer between PV panels and air which is the main cause for increase in the temperature of PV panels and decrease in the temperature of the air leaving the cavity.

Table 1 describes the main scenarios that were investigated before installation of the façade system in Reading and the generated electricity. The simulation results reveal that among the studied scenarios, the arrangement of PV modules does not have a significant effect on the amount of generated electricity.

<table>
<thead>
<tr>
<th>Scenario No</th>
<th>Arrangement/Geometry</th>
<th>Air cavity size (mm)</th>
<th>Annual generated electricity of all six CSI modules (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>150</td>
<td>562.2</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>250</td>
<td>562.1</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>150</td>
<td>562.3</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>250</td>
<td>562.1</td>
</tr>
</tbody>
</table>

2.3 Experimental results and numerical model verification

Based on the described preparatory studies, in order to investigate the actual thermal and electrical performance of the PV ventilated façade system in real conditions, an experimental study has been set up at the University of Reading. The experiment includes six Crystalline Silicon (c-Si) modules in two rows and three columns, which are installed on a South facing wood wall adjacent to the experiment shed. The 150 mm air cavity between the PV modules and 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 horizontal gap (10 mm) between the first and second rows of the panels.

The developed model for simulation of the performance of PV ventilated façades was verified using the experimental results. Comparing the simulation and experimental results revealed a good correlation between these two sets of data. In terms of PV surface temperature, there was a 0.8 °C average deviation between the simulation and experimental results. In addition, the deviation between the actual generated
The ultimate aim of the simulation is to provide the information required for the design and arrangement of the ventilated façade system in Izmir, Turkey. In order to achieve this task, the numerical simulation needs to be verified before being used for the modelling of the PV façade in Izmir. Generated electricity, PV surface temperature and the velocity of air passing through the cavity in a natural ventilation regime are the most crucial factors, which are considered in the verification process. In terms of electricity generation rate, the comparison between the simulation results and the experiment is demonstrated in Figure 3 (left). This figure shows a very close match between the outcomes of simulation and those recorded in the experiment with 6.5% deviation in the amount of electricity generated and the estimated value in the simulation.

The comparison between the back surface temperatures of the PV modules in simulation and experiment revealed a good correlation between simulation and experiment results. Considering all six PV modules, there is a 0.8 °C average deviation between the simulation and experiment results. Figure 3 (right) provides clearer illustration for the simulation and experiment results in terms of back surface temperature of the PV modules for module 6. It shows that the maximum difference happens in high irradiation conditions in which the simulation prediction is up to 4°C higher than experimental results. Finally, the air velocity within the cavity is the most challenging factor, which is taken into account for verification of the simulation. The challenge is mainly due to the fluctuating nature of the air velocity within the cavity of the PV façade. In order to make a clear picture and show the trend of the ever changing air velocity within the cavity, the best polynomial function is fitted to both experimental and simulation results associated with one of the modules (module 5) using the Least Squares (LS) method. Considering the fluctuating nature of air velocity in the cavity of the PV façade, it was demonstrated a reasonable correlation between simulation and experiment results for this challenging parameter.

3 Results and design guide for final prototype

Based on the good correlation between the simulation and experimental results in Reading, the same approach was adopted in the numerical modeling of BIPV prototype in Izmir, Turkey. Taking into account the geometry of the candidate building façades, the targeted capacity of the PV façade system and the most aesthetical solutions, 24 main arrangement scenarios were investigated and the most appropriate design
solution was recommended for the installation of the ventilated façade system in the campus of Yasar University in Izmir, Turkey.

3.1. Candidate buildings for installation of PV façade system at Yasar University. BIPV design.

Initially, there were two main buildings (L and O buildings) and four façades (southwest and southeast façades of the buildings) under consideration for application of the BIPV system (See Figure 4).

![Fig. 4 Sketch of the buildings under consideration and related façades. Buildings L and O initial arrangement of PV modules for maximum power installed capacity (west and south façades)](image)

Considering the key parameters including site location, climatic parameters and BIPV system characteristics (azimuth, etc.), preliminary estimations of the number of BIPV modules and their associated annual electricity generation rates have been conducted. Figure 4 demonstrates the arrangements of the BIPV system considering the maximum practical power installed capacity of the system on each candidate façades of buildings L and O respectively. In addition, the estimated annual electricity generation rate associated with these PV arrangements for buildings L and O are respectively provided in Table 2.

Among the potential buildings that could be considered in the campus of Yasar University, Southeast and Southwest façades of building L were chosen as final candidates.

Table 2. Preliminary results for Buildings L and O

<table>
<thead>
<tr>
<th>BUILDING</th>
<th>ORIENTATION</th>
<th>GLASS UNITS</th>
<th>TOTAL AREA (m²)</th>
<th>TOTAL POWER (Wp)</th>
<th>TOTAL ENERGY (Kwh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>South</td>
<td>144</td>
<td>172.8</td>
<td>22,320</td>
<td>20,407</td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>56</td>
<td>67.2</td>
<td>8,680</td>
<td>7,534</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>200</td>
<td>240.0</td>
<td>31,000</td>
<td>27,941</td>
</tr>
<tr>
<td></td>
<td>West I</td>
<td>104</td>
<td>124.8</td>
<td>16,120</td>
<td>13,824</td>
</tr>
<tr>
<td></td>
<td>West II</td>
<td>78</td>
<td>93.6</td>
<td>12,090</td>
<td>10,304</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>84</td>
<td>100.8</td>
<td>13,120</td>
<td>11,876</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>266</td>
<td>319.2</td>
<td>41,230</td>
<td>36,004</td>
</tr>
</tbody>
</table>
3.2. Arrangement and simulation of PV modules and studied scenarios

For a ventilated façade with 6 kWp PV modules in Yasar University, different arrangements of the PV modules for the two candidate building façades were considered. Taking into account the geometry of the candidate building façades, the targeted capacity of the PV façade system together with the most aesthetical solutions, six main arrangements were identified. Each arrangement includes one Dye-Sensitized cell (DSC) and 39/40 Crystalline Silicon (c-Si), which respectively account for 1.5 and 6045/6200 Wp power. Considering the six arrangements of the PV modules on the candidate façades together with two different depths (150 and 250 mm) for the air cavity between the modules and building façade, 12 different scenarios were identified.

Simulation of the twelve arrangements of both DSC and c-Si modules in the campus of Yasar University has been conducted using TRNSYS [2] and TRNFLOW [3] simulation packages by considering the Meteonorm weather data for Izmir, Turkey (TRNSYS, 2010). The outcomes of these numerical simulations shows that by installation of the system on the Southeast facing façade, the annual generated electricity of c-Si and DSC modules is increased between 1.8-3.3% compared to the Southwest façade. This is mainly due to the higher annual irradiation level on the southeast facing façade. The profile of electricity generation for both c-Si and DSC modules demonstrates that the power generation rate for both modules is following the trend of irradiation on PV installation surfaces. For the fifth scenario, this trend is shown in Figure 5.

![Figure 5](image)

**Fig 5.** Power generated by c-Si PV modules in the fifth scenario and the irradiation level on the PV modules according to the Meteonorm database for Izmir.

On the other hand, the simulation outcomes of 24 different design solutions revealed no significant correlation between either the depth of air cavity or the airflow rate within the cavity and the electrical performance of the system. However, both the depth of air cavity and the arrangement of air openings at the top and bottom of the ventilated façade significantly influence the airflow rate passing through the cavity of the PV façade system.

4 Conclusions

The ultimate aim of these works was the design and construction of a PV system integrated in a ventilated façade. By integration of test PV modules in a test site at the University of Reading, the performance of the ventilated façade system was assessed using both experimental and numerical simulation. After verification of the numerical model using experimental results, the developed model was reliably used in
the design and arrangement of the prototype ventilated façade to be installed at Yasar University. In order to identify the most promising façade for installation of the system, 24 different design solutions/scenarios were investigated for DSC and c-Si PV modules. Finally, considering the electrical efficiency and the thermal characteristics of the system under each scenario, the most appropriate design solution has been proposed for installation of a 6 kWp PV ventilated façade system in Izmir, Turkey. To this end, the following are the summary of the research activities and remarkable conclusions for the comprehensive study of the PV ventilated façade system in this project:

- 1600mm X 750mm double laminated crystalline 4mm/4mm tempered BIPV units were successfully fabricated and tested in Reading as prototypes of ventilated façade.
- Six c-Si modules were installed and thermal and electrical performance of the system was experimentally studied in a test ventilated façade at the University of Reading. In addition, a numerical model was developed to assess both thermal and electrical performance of the ventilated façade system.
- The developed model for simulation of the performance of PV ventilated facades was verified using the experimental results. Comparing the simulation and experimental results revealed a good correlation between these two sets of data. In terms of PV surface temperature, there was a 0.8°C average deviation between the simulation and experimental results. In addition, the deviation between the actual generated power and prediction was less than 6.5%.
- Based on the good correlation between the simulation and experimental results in Reading, the same approach was adopted in the numerical modelling of BIPV prototype in Izmir, Turkey. Taking into account the geometry of the candidate building façades, the targeted capacity of the PV façade system, together with the most aesthetical solutions, 24 main arrangement scenarios were investigated and the most appropriate design solution was recommended for the installation of the ventilated façade system in the campus of Yasar University in Izmir, Turkey. The outcomes of simulation of 24 different design solutions revealed that both the depth of air cavity and the arrangement of air openings at the top and bottom of the ventilated façade significantly influence the airflow rate passing through the cavity of the PV façade system.

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References