1 INTRODUCTION

1.1 The Aesthetic Energy Roof (AER) concept

The future of the European photovoltaic industry depends heavily on breakthroughs in 'mass customization' of photovoltaic roofs, that require the local execution of engineering, on-demand manufacturing and on-site delivery, and that need a high level of aesthetics to appeal to a broad public.

In line with this vision, the AER concept is based on the patent-pending idea to use the photovoltaic glass itself for the watertight connection between the PV panels. In this way a watertight PV roof can be constructed using an absolute minimum of required installation materials. As a bonus, no frame or mounting materials are visible around the glass thereby boosting the roof’s aesthetic value.

In order to understand and improve the Aesthetic Energy Roof’s electrical performance, we decided to focus first on its thermal behavior.

Fig. 1 Photograph of the first Aesthetic Energy Roof of AERspire.

1.2 Thermal behavior of building integrated PV

It is well-known that building integrated PV systems show higher operating temperatures and resulting lower electrical yields than non-integrated systems. Zomert et al. [1] quantified this effect for the Brazilian climate and found 7% lower electrical performance for integrated PV system compared to a non-integrated PV system.

The ventilation shaft between PV panels and roof support structure is essential to draw away the heat of the PV panels and ensure a good electrical output. Duffie and Beckman [2] and Zondag [3] have made insightful reviews of the theory and experiments related to the thermal modeling of PV systems.

Brinkworth [4] developed a model to estimate the optimum gap distance between the PV panels and roof support structure. The model was validated using measurement data. An optimized roof-length-to-air-gap ratio of 20:1 was found. Similarly, Gan et al. [5] simulated the optimum air gap and found that it should be bigger than 15 cm for a 2 panel long duct.

Tonui [6] researched options to improve the heat transfer towards the air duct by applying metal fins in the air gap. By this method they were able to lower the PV panel temperature by up to 2 degrees at 800 W/m² irradiance.

Pantic [7] investigated the use of the heated air from three different BIPV configurations on the energy performance of the building. Finally, Guitavarch [8] made a correlation between the performance of the building integrated PV panels and the level of integration.

Despite the numerous studies cited above, a clear view on the thermal behavior of building integrated PV systems in the European climate is still missing. In particular, there is a lack of data for the specific AER roof concept in the Benelux application area.

1.3 Objective of the paper

In this paper we will investigate the thermal behavior of the AER system. Our objective is to understand the heat flows in the building integrated PV system and to see to what degree we can influence the PV panel temperature by engineering of the ventilation shaft within the AER concept. In the paper we will apply a combination of experimental work and simulations.

We will first develop a theoretical model on the heat flows of the roof in section 2. Next, in section 3, we will describe the experimental setup that we used. Section 4 shows results from both the measurements and the simulation. Finally, in section 5 the conclusions of the research will be drawn.
2 THERMAL MODEL

2.1 The model

Figure 2 schematically shows the heat balance of a building integrated PV system. Solar radiation hits the PV panel surface and is mainly absorbed in the crystalline silicon cells. The generated heat can leave via three paths: Through the front glass (\(Q_{\text{Front}}\)), through the roof support structure beneath the panels (\(Q_{\text{Indoor}}\)), and upwards through the ventilation shaft eventually leaving the roof via the ridge (\(Q_{\text{Ventilation}}\)).

Fig. 2 Schematic drawing of the heat flows of a building integrated PV system.

We developed a simulation model on the basis of an equivalent circuit for the heat flows through the building integrated photovoltaic roof that is depicted in figure 3. Each path is characterized by a number of thermal resistances that will be explained in the next subsection.

2.2 The equations

The thermal conductance from the cell towards the PV panel surface \(R_{\text{Cond,front}}\) can be described by the specific conductances of the encapsulation and glass materials as in Eq. (1).

\[
R_{\text{Cond,front}} = \frac{1}{\frac{h_{\text{Glass}}}{k_{\text{Glass}}} + \frac{h_{\text{PVa}}}{k_{\text{PVa}}}} \tag{1}
\]

The convective heat transfer from the PV panel surface to the ambient air \(R_{\text{conv,front}}\) is a combination of free convection and forced convection as shown in Eq. (2). For our description of free convection we followed Armstrong and Hurley [8] and for the description of forced convection we follow Watmuff et al. [9].

\[
R_{\text{Conv,front}} = 1/(\sqrt{h_{\text{Glass}} + h_{\text{PVa}} - A_{\text{PV}}} \cdot A_{\text{PV}}) \tag{2}
\]

For the radiative heat transfer from the PV panel front glass to the sky \(R_{\text{rad,front}}\) we used the Stephan-Boltzmann law linearized for the temperature difference \(T_{\text{PV,front}} - T_{\text{sky}}\), thus arriving at Eq. (3).

\[
R_{\text{rad,front}} = (\varepsilon_{\text{glass}} \cdot \sigma \cdot A_{\text{PV}} \cdot (T_{\text{PV,front}} - T_{\text{sky}}) \cdot (T_{\text{PV,front}} + T_{\text{sky}}))^{-\frac{1}{4}} \tag{3}
\]

As we have a symmetrical glass-glass PV panel build up, the heat conductance to the back of the PV panel is equal to that of the front, i.e. \(R_{\text{cond,front}} = R_{\text{cond,back}}\). The radiative resistances \(R_{\text{rad,airgap}}\) and \(R_{\text{rad,insu}}\) are calculated in a similar manner to \(R_{\text{rad,front}}\) in Eq. (3). For the roof support structure and insulation package a similar equation as Eq. (1) is used, in this case with the insulation materials’ specific conductances and thicknesses as input.

Finally, the thermal resistance of the ventilation air flow through the roof ridge \(R_{\text{airflow}}\) was calculated by the air flow \(v\), heat capacitance \(c\), air density \(\rho\), and length-to-depth ratio of the ventilation shaft \(L/D\).

\[
R_{\text{airflow}} = \rho c v L D \tag{4}
\]

For the heat source \(Q_{\text{cell}}\) we took 90% of the in-plane irradiance \(G\), thus assuming a thermal reflection of 10%. Furthermore, we assume zero electricity flow, i.e. PV panels in open-circuit condition. A Python script was written to calculate the various temperatures \(T_{\text{PV,front}}, T_{\text{cell}}, T_{\text{PV,back}}, T_{\text{airgap}}, T_{\text{PV,back}}, T_{\text{insu,outdoor}}\) and \(T_{\text{insu,indoor}}\) in °C using Kirchhoff’s Current Law solved by the inverse matrix method.

2.3 Typical input numbers

Typical input parameters used in the modeling were based on the AER design and given in Table I.

Table I Typical input parameters used in the model calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance (W/m²)</td>
<td>800</td>
</tr>
<tr>
<td>Ambient temperature °C</td>
<td>20</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>1</td>
</tr>
<tr>
<td>Air gap flow speed (m/s)</td>
<td>0.5</td>
</tr>
<tr>
<td>Air gap depth (m)</td>
<td>0.1</td>
</tr>
<tr>
<td>Air gap length (m)</td>
<td>3.3</td>
</tr>
<tr>
<td>Thermal reflectance</td>
<td>10%</td>
</tr>
</tbody>
</table>

Fig. 3 Equivalent circuit for the heat flows within a building integrated PV system.
3 EXPERIMENTAL SETUP

3.1 PV system

Key to the AER concept is the use of frameless glass-glass panels in which the cells are laminated in between front and back glass plates. For the batch of PV panels under study we chose 2.8 mm glass from Ducatt for both front- and back side of the panel. For the reference group, conventional PV panels were constructed using white TPT foil as back cover.

Each panel consisted of 60 multicrystalline silicon cells with two busbars and from a single power class. In the division of the cells between the panels the ‘neighbouring wafer’-principle was followed to arrive at fully comparable panels. Each panel was characterized in a h.a.l.m. flasher before and after exposure to natural sunlight for one week. The light induced degradation was less than 1%. The PV panel power after light soaking ranged from 220-230 Wp.

The PV panels were mounted on a south oriented conventional on-roof materials and monitored by environmental data using an ECO instruments multiplexer and IV tracer. With environmental data gathered by a weather station equipped with high accuracy measurement tools that collected data in between IV scans the PV panels were kept at open-circuit. Once every minute, synchronized I-V scans with 4 wire sensing and duration of 2 seconds and 256 data points were recorded and logged in a computer together with environmental data using an ECO instruments multiplexer and IV tracer.

For each PV panel there was a T type Teflon thermocouple integrated in the PV panel during fabrication. The thermocouples were placed directly behind a cell near the panel’s center. The setup also included a thermocouple to measure the temperature of the ambient air in the ventilation shaft. This thermocouple was positioned inside the shaft, about midway across the 1 m width of the shaft, about 60 cm from the roof ridge across the 3.3 m length of the shaft and about 2 cm from the roof support across the 10 cm height of the shaft.

3.2 Data acquisition system

The outdoor test facility was equipped with high accuracy measurement tools that collected data throughout the day in one minute intervals. Solar irradiance was measured by an in-plane mounted pyranometer (MS-802, Secondary standard). Environmental data was gathered by a weather station (WS-500) that collected data for ambient temperature, relative humidity, wind speed and wind direction.

In between IV scans the PV panels were kept at open-circuit. Once every minute, synchronized I-V scans with 4 wire sensing and duration of 2 seconds and 256 data points were recorded and logged in a computer together with environmental data using an ECO instruments multiplexer and IV tracer. For each PV panel there was a T type Teflon insulated thermocouple integrated in the PV panel during fabrication. The thermocouples were placed directly behind a cell near the panel’s center. The setup also included a thermocouple to measure the temperature of the air in the ventilation shaft. This thermocouple was positioned inside the shaft, about midway across the 1 m width of the shaft, about 60 cm from the roof ridge across the 3.3 m length of the shaft and about 2 cm from the roof support across the 10 cm height of the shaft.

3.3 Data analysis procedures

The performance ratio of the PV panels was calculated on a daily basis according to Eq. (5). The PV power flashed after light soaking was used as basis for the calculation. Other quantities in the equation are \( G_{\text{STC},\text{flash}} = 1000 \, \text{W/m}^2 \) and the power \( P_i \) and in-plane irradiance \( G_i \) measured in one-minute intervals.

\[
P_{\text{mod},i} \sum \frac{P_i}{G_i} = \frac{G_{\text{STC},\text{flash}}} {G_{\text{STC},\text{mod}}} \sum P_i \quad (5)
\]

The temperature of the panels was calculated on a daily basis according to Eq. (6). Here, the panel temperature measured in one minute intervals \( T_{\text{mod}} \) was weighed by the in-plane irradiance \( G_i \).
\[ \dot{V}_{\text{red}} = \frac{\sum G T_{\text{mod},i}}{\sum G} \]  

(6)

\[ \dot{U} = \frac{0.9 \times \dot{G}}{T_{\text{mod}} - T_{\text{amb}}} \]  

(7)

4 RESULTS AND DISCUSSION

4.1 Comparison between the open-rack, on-roof and in-roof systems.

The daily values of performance ratio, panel temperature and \( U \)-value of the six systems described in section 3.1 are shown in figure 5(a)-(c).

![Figure 5](image_url)

**Fig. 5** Daily values of the various systems for the reported measurement period from June 17th to July 30th, for (a) the panel temperature \( T_{\text{mod}} \), (b) the \( U \)-value, (c) the performance ratio \( PR \).

The large scatter in day-to-day variation of \( T_{\text{mod}} \) makes it difficult to draw direct conclusions from Fig 5(a). In contrast, group differences in \( PR \) and \( U \)-value shown in Fig 5(b)-(c) are much clearer visible, as these parameters are less weather-dependent.

In order to correct for these influence of the day-to-day weather changes we determined group averages by looking at their relative values per day (i.e. a two-factor ANOVA analysis method using factors date and group). Table II reports on the group averages for the complete reported measurement period.

<table>
<thead>
<tr>
<th>System</th>
<th>PR [%]</th>
<th>( T_{\text{mod}} ) [°C]</th>
<th>( U )-value [W/m²K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference system</td>
<td>90.2</td>
<td>48.1</td>
<td>19.0</td>
</tr>
<tr>
<td>Open rack</td>
<td>91.7</td>
<td>47.7</td>
<td>19.1</td>
</tr>
<tr>
<td>On-roof</td>
<td>89.1</td>
<td>49.4</td>
<td>18.1</td>
</tr>
<tr>
<td>In-roof, open</td>
<td>89.8</td>
<td>49.7</td>
<td>17.6</td>
</tr>
<tr>
<td>In-roof, regular</td>
<td>87.7</td>
<td>54.4</td>
<td>16.0</td>
</tr>
<tr>
<td>In-roof, closed</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All-in-all a consistent behavior can be observed throughout Figs 5(a)-(c) and Table II: The open-rack system is the best ventilated system, the opened roof and regular roof show very similar performance, and the closed roof is the least ventilated system.

The table makes clear that there is a very strong correlation between \( PR \) and \( U \)-value. It allows a direct quantification of the electrical output to the ventilation level, and leads to the following rule-of-thumb for summers in the Dutch/Belgian climate: An increase of the \( U \)-value by 1 W/m²K leads to an improvement of the \( PR \) by 1%.

Furthermore, the table surprisingly shows that the difference in thermal performance between the ‘AER regular in-roof’ and the ‘AER opened-ridge in-roof’ groups is very small. Apparently, in the AER regular in-roof group, the design of the roof ridge is not a limiting factor in the heat loss. In the following sections we will investigate this phenomenon by making use of the thermal model described in section 2.

4.2 Comparison between model and measurement

In this section we will perform a detailed comparison of the measurements and our simulation model for the in-roof system. We chose July 9th for this investigation, which was a typical clear-sky summer day on which we performed a unique experiment. In the first half of this day the AER in-roof system was in its ‘closed-ridge’ state. Around 15.30hrs, we removed the insulation foam material and thus put the system in its ‘opened-ridge’ state. This meant we could monitor the transient switch between the two roof states and thus were able to obtain a direct measure for the importance of the heat loss through the ventilation shaft \( Q_{\text{ventilation}} \).

![Figure 6](image_url)

**Fig. 6** Measured and modeled panel and air gap temperature for the in-roof system on July 9th, 2013.
Figure 6 shows that the elevation of the cell temperature above ambient evolved in a parabolic-like profile over the course of the day, with its maximum around noon. A good agreement in cell temperature can be seen between model and measurement. Upon opening the roof at 15.30 hrs the cell temperature dropped by 5°C in both measurement and model.

The measured and modeled air gap also show a sharp drop in temperature around 15.30 hrs. No perfect agreement between model and measurement could be observed: The modeled air gap temperature was about 20-40% lower than the measured air gap temperature. To understand this difference we measured the air gap temperature with a mobile measurement apparatus on various positions along the air shaft. We found that the temperature in the air gap developed approximately linearly over the length of the ventilation shaft, from the ambient air temperature near the air entrance at the roof’s gutter to the final air gap temperature near the air exhaust at the roof’s ridge. In this respect, note that our one dimensional model delivered by definition an average air gap temperature of the whole system, i.e. corresponding to 50% of the exhaust temperature. Furthermore, note that our air gap measurements were performed at 60 cm from the shaft exhaust, meaning they corresponded to about 80% of the exhaust temperature. The different locations at which the air gap temperature were modelled and measured can thus fully explain the observed difference between model and measurement of 20-40%.

The model appeared to be a more accurate predictor of the average air gap temperature than the measurement itself.

4.3 Modeled heat flows for the in-roof system

For the typical input parameters of the in-roof system given in Table I, the modeled heat flows and U-values are shown in Table III. The table shows that 76% of the heat is lost through the front side of the PV panel (\(Q_{	ext{front}}\)). For the 24% lost to the back, there is a more or less even division between heat lost through the ventilation shaft and by conductance through the roof’s insulation package into the indoor room. Here, it must be stressed again that our roof was not insulated and consequently showed a low \(R\)-value of \(R_{\text{cond.insu}} = 0.26\).

Table III. Calculated temperatures and heat flows for the thermal network of Fig. 3 and the input parameters of Table I.

<table>
<thead>
<tr>
<th>Loss channel</th>
<th>Symbol</th>
<th>U (%/K)</th>
<th>(Q) (W/m²)</th>
<th>(U) (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front side</td>
<td>(Q_{\text{front}})</td>
<td>76</td>
<td>548</td>
<td>12.2</td>
</tr>
<tr>
<td>Back side</td>
<td>(Q_{\text{back}})</td>
<td>24</td>
<td>172</td>
<td>3.8</td>
</tr>
<tr>
<td>Roof insulation</td>
<td>(Q_{\text{insul}})</td>
<td>11</td>
<td>76</td>
<td>1.7</td>
</tr>
<tr>
<td>Ventilation</td>
<td>(Q_{\text{ventila}})</td>
<td>13</td>
<td>96</td>
<td>2.1</td>
</tr>
</tbody>
</table>

The corresponding calculated thermal resistances are shown in Table IV. From this table it becomes insightful what the limiting step in the thermal flows is. From the low value of \(R_{\text{airgap}}\) it is clear that there is a good radiative heat transfer from PV panel to the supporting roof structure. Also from the low value of the ventilation air flow \(R_{\text{airflow}}\) is clear that heat can easily escape through the air gap for the given air flow speed of 0.5 m/s. However, the calculated \(R_{\text{airgap}}\) has a very high value of 0.42 Km²/W. This means that the modeled limiting step is the coupling of the heat from the PV panel into the air flow.

Table IV. Typical thermal resistance values calculated using the input parameters of Table I.

<table>
<thead>
<tr>
<th>Thermal Resistance</th>
<th>Symbol</th>
<th>(R)-value [m²·K/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiative heat transport</td>
<td>To the front</td>
<td>(R_{\text{rad front}})</td>
</tr>
<tr>
<td>To the air gap</td>
<td>(R_{\text{rad airgap}})</td>
<td>0.14</td>
</tr>
<tr>
<td>To the indoor</td>
<td>(R_{\text{rad insu}})</td>
<td>0.21</td>
</tr>
<tr>
<td>Conductive heat transport</td>
<td>To the front</td>
<td>(R_{\text{cond front}})</td>
</tr>
<tr>
<td>To the back</td>
<td>(R_{\text{cond back}})</td>
<td>0.0030</td>
</tr>
<tr>
<td>To the indoor</td>
<td>(R_{\text{cond insu}})</td>
<td>0.26</td>
</tr>
<tr>
<td>Convective heat transport</td>
<td>To the front</td>
<td>(R_{\text{conv front}})</td>
</tr>
<tr>
<td>To the back</td>
<td>(R_{\text{conv airgap}})</td>
<td>0.42</td>
</tr>
<tr>
<td>To the indoor</td>
<td>(R_{\text{conv insu}})</td>
<td>0.34</td>
</tr>
<tr>
<td>Airflow in ventilation shaft</td>
<td>(R_{\text{airflow}})</td>
<td>0.17</td>
</tr>
</tbody>
</table>

5 CONCLUSIONS AND RECOMMENDATIONS

In conclusion, we reported on a direct comparison of PV systems with various ventilation levels in a field test located in the north east of Belgium. The systems were constructed using the patent-pending Aesthetic Energy Roof (AER) concept that is able to realize a watertight connection between adjacent frameless glass-glass panels.

A clear difference in ventilation level for the studied systems was observed and quantified by their \(U\)-values, i.e. their ability to lose heat. In order from best ventilated to least ventilated we have investigated:

1. An open rack mounted system with frameless glass-glass AER panels \((U = 21.7 \text{ W/m}^2\text{K})\).
2. An on-roof mounted system with frameless glass-glass AER panels and an air gap of approx. 10 cm \((U = 19.1 \text{ W/m}^2\text{K})\).
3. An on-roof reference system \((U = 19.0 \text{ W/m}^2\text{K})\).
4. An in-roof mounted system with frameless glass-glass AER panels and air gap of 10 cm, with a. opened gutter and ridge \((U = 18.1 \text{ W/m}^2\text{K})\) b. regular gutter and ridge \((U = 17.6 \text{ W/m}^2\text{K})\) c. closed gutter and ridge \((U = 16.0 \text{ W/m}^2\text{K})\).

A strong correlation between the \(U\)-value and performance ratio of the system was found. The difference in performance ratio between on-roof mounting and in-roof mounting was only 2%. This slight drop in performance for the in-roof system is more than compensated by its superior aesthetics and additional cost savings by omitting the regular roof tiles. We therefore conclude that the building integrated AER system shows good electrical performance and is ready for commercial roll-out.

In order to understand the results for the in-roof system we developed a one dimensional analytic thermal model. The model showed good correspondence to the measurement data and was able to quantify the heat flows in the in-roof system, in which about three quarters of the energy is lost to the front side of the panel, and one eighth each is lost through the ventilation shaft and roof support structure.

From the model a clear recommendation can be given...
in the further optimization of the AER in-roof system: Key improvements should focus on the heat transfer from PV panel into the air flow in the ventilation shaft. One possible development track is to ensure a good thermal conductance to the mounting clamps and aluminum mounting bars in order to use the mounting materials as heat sinks. Another possible development track is to engineer a smart ventilation air flow with enough turbulence near the modules to pick up the heat. A third possible development track is to improve the module design, by enhancing the effective surface area on the back side or by using special module materials with high thermal conductance.

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REFERENCES


