The Characterisation of Photovoltaic-Integrated Building Facades Under Realistic Operating Conditions

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ABSTRACT: This paper presents the results from a combined experimental and simulation analysis of a prototype photovoltaic facade when subjected to conditions typical of UK climate seasons. The departure of the electrical efficiency from peak published values is measured and the efficiency improvement associated with facade operation in combined power and heat recovery mode is estimated.

KEYWORDS: PV facades; SOLINFO; ESP-r; model calibration.

1. INTRODUCTION

The EC Solar "House" project involves the incorporation of energy conserving components within a range of contemporary building projects throughout Europe. The intention is to demonstrate that such components can be harnessed without compromising accepted design principles. To assist with component optimisation/integration, and ensure that one performance aspect (e.g. lower electricity costs through the use of photovoltaic facades) is not attained at the expense of another (e.g. increased lighting use because of reduced daylight penetration), a technical support service has been established. This service utilises the ESP-r system to appraise a building's overall energy and environmental performance. The support service is situated at the University of Strathclyde and operates under the direction of the SOLINFO programme [1].

This paper reports on one "consultancy" undertaken by the service, entailing an assessment of the operational efficiency of photovoltaic (PV) cells when encapsulated within a prototype building facade allowing cavity heat recovery*. The expectation is that such facades, when applied to commercial buildings, will enhance the thermal performance of the building envelope, and provide an economic delivery of electric power and heat. The design of such facades is complicated by the exposure of the PV cells to conditions which may be at variance to those required for optimal output.

2. PV MODULE PERFORMANCE CHARACTERISATION

The tested module (0.496 m^2) comprised 24 mono-crystalline cells (0.336 m^2) of BP Solar's high efficiency cell variety [2] sandwiched between two layers of clear float glass bonded together with a transparent resin. Other manufacturers have developed similar glazed modules and, with minor parameter adjustments, the results of this work should be applicable to these systems.

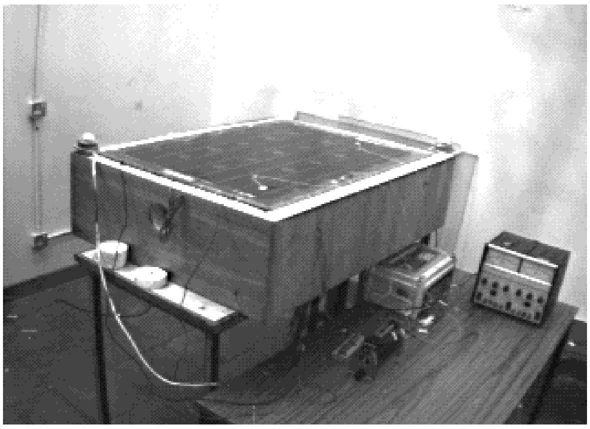

Figure 1: PV test rig.

The module was subjected to testing (Figure 1) in a solar simulator consisting of an array of filtered dichroic tungsten lamps, with corrections corresponding to an air mass of 1.5. Test objectives were to:

- determine the effect of temperature on cell efficiency;
- assess the enhanced efficiency associated with cell cooling and cavity heat recovery;
- support the development of a mathematical model of the PV facade for use in estimating outdoor performance with the ESP-r system.

The irradiance level chosen for the performance characterisation was 600 W/m^2 as this is representative of the mean peak irradiance on a vertical plane in the UK. Figure 1 shows the test rig arrangement: a 0.83m × 0.57m × 0.125m deep box comprising a 5mm plywood exterior,

* Solar House Project JOU2-CT93-0336: *The research and development of PV modules and system components for the cladding of commercial building in Europe*. Project team: IT Power, Eversley, BP Solar, Sunbury-on-Thames, Ove Arup & Partners, Newcastle-upon-Tyne, Christian Pohl Gmbh, Koln, Fraunhofer Institute, Freiburg and the Newcastle Photovoltaics Applications Centre, Newcastle-upon-Tyne.

with 50mm polystyrene foam insulation and a 5mm plywood interior painted black on the absorbing surfaces.

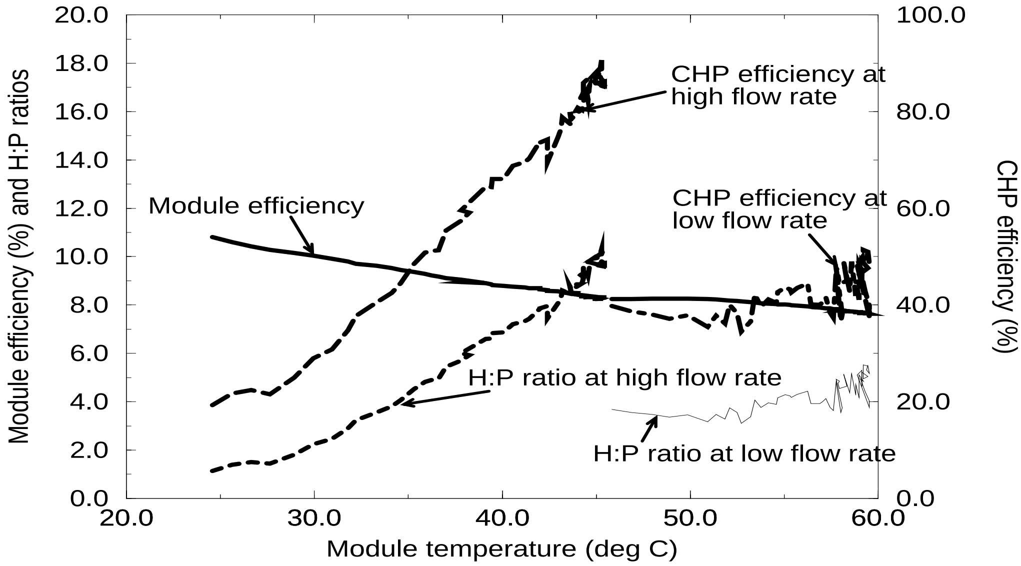

Figure 2: Experimental results.

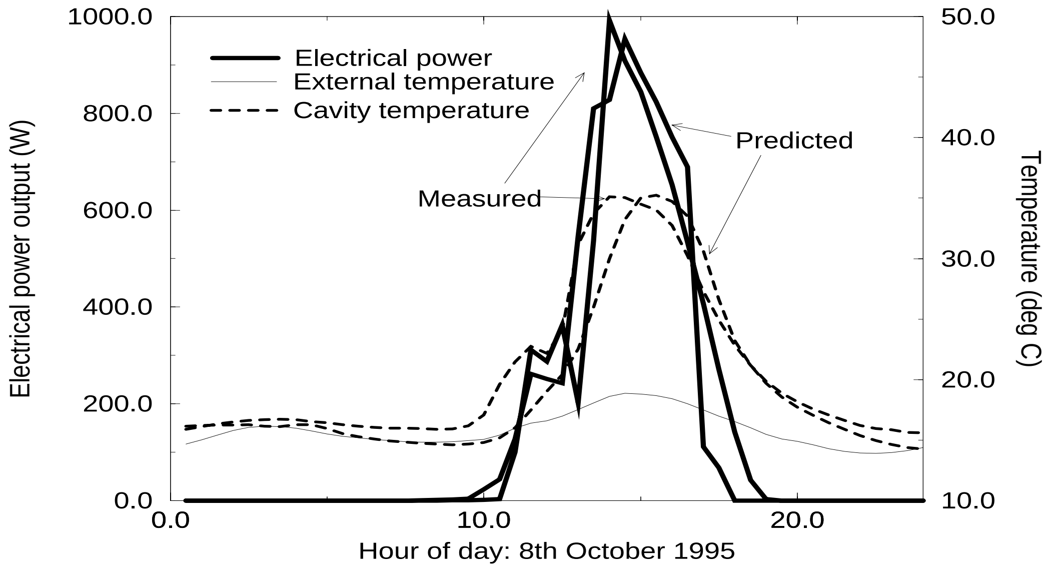

Figure 3: ESP-r predictions v. PASLINK cell measurements.

In order to characterise the range of possible operating conditions, three distinct cavity ventilation regimes were considered corresponding to stagnant, low and high ventilation rates. Figure 2 summarises the results for each regime (H:P is the heat-to-power ratio; CHP is combined heat and power).

From the results, the module's electrical power output can be seen to decrease with increasing temperature at a rate equivalent to 0.455%/°C, corresponding to a specific power drop of 0.145 W/°C. (This is at the high end of the 0.35-0.45%/°C expected for silicon based cells) [3] (although other workers have claimed that these cells have among the best high temperature performance characteristics for commercially available cells).

2.1 PV Panel Mathematical Model

On the basis of the experimental results, a mathematical model of the PV module was developed [4] and integrated within the ESP-r program. The model represents the physical system as a set of series and parallel connected p-n junctions. The data required by the model are the short-circuit current, the open circuit voltage, the voltage and current at the maximum power point, the reference values at which these are measured (usually 1000 W/m^2 and 25°C), and the number of series and parallel connected cells in each panel. In addition, an empirical constant (as in previous section) is required to account for the change in output with change in temperature [5].

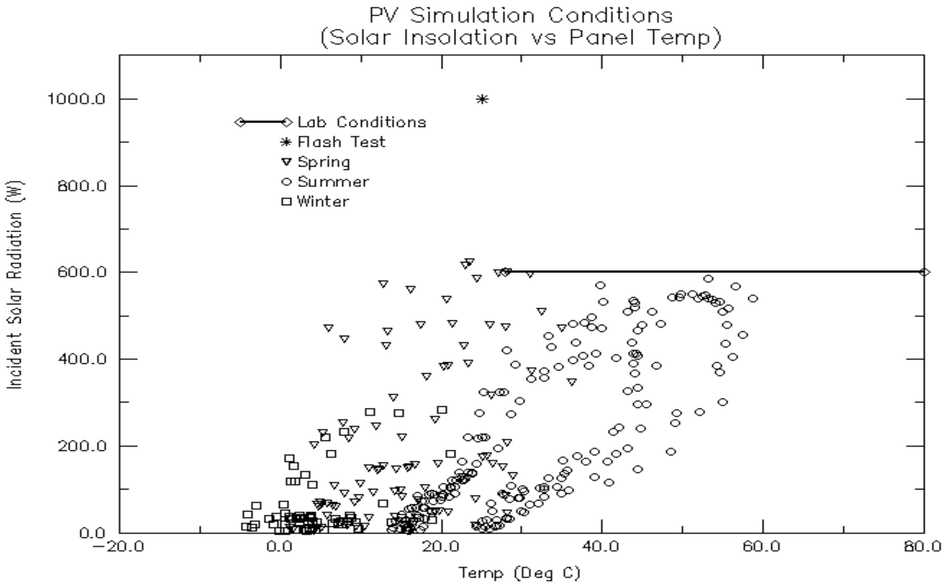

Figure 4: PV panel simulation conditions.

At each simulation time step, the incident solar radiation and nodal temperatures are computed by ESP-r. This allows the electrical power output to be calculated. In turn, this power take-off is included within the energy balances at the nodes representing the PV material. By integrating the PV model with ESP-r's building fabric and air flow models, it is possible to determine the electrical and thermal efficiencies.

To validate the PV model and the thermal/electrical interactions would be a lengthy procedure. Instead, a model calibration exercise was undertaken in which predictions were compared to measurements over a reasonable operating range: if the level of agreement is acceptable, or if such agreement is obtained after justified changes to the model are made, then "scaling" to realistic buildings can proceed. Calibration can be considered at a number of different levels, depending on the eventual use of the model. An analogy can be made with the calibration of a temperature sensor. If a sensor is checked against a reference at only one temperature, then it is possible to use this sensor for limited measurements around this temperature level (a low-level calibration). If the sensor is checked at limits such as 0°C and 100°C then the sensor can be used within this range, but with the uncertainty caused by the assumption of linearity (an intermediate-level calibration). Finally, if the sensor is checked at a number of intermediate temperatures and the full calibration curve obtained, then the sensor can be considered to be fully calibrated (a high-level calibration).

Two calibrations were carried out in the present study. Firstly, a check was made on the electrical power output predicted by the PV model. Measured data from the laboratory test was compared with model predictions and the empirical constant determining the temperature dependence of the power output was varied until a reasonable agreement was obtained. Secondly, predictions were compared with measured data from a PASLINK test cell [6] experiment. In this case, the calibration was carried out on days of high and low solar radiation for a range of air flow rates within the PV module. Both electrical and thermal performance were considered. Results for the case when the module was sealed are shown in Figure 3.

2.2 Simulated Practical Performance

After model calibration, the performance of the prototype facade was simulated under typical UK conditions. Figure 4 shows the predicted PV cell temperatures plotted against incident irradiance: these conditions are significantly removed from those comprising a standard pulse test (25°C and $1000W/m^2$), while the conditions of the laboratory tests are at the upper end of those expected under UK climate conditions.

Figure 5 shows the predicted facade performance under summer conditions, corresponding to an average PV cell temperature of 32.5°C.

Finally, Table I summarises the effective operating efficiencies by season and for the electrical power only and combined heat and power cases.

3. CONCLUSIONS

It has been shown that the operational electrical efficiency of the tested PV facade module is less than the peak published data at 11%: this is in agreement with the manufacturer's published data for their high efficiency product. This efficiency can be improved significantly if the cells are cooled and heat recovered. Even during winter operation, when thermal demands are at their highest, the combined efficiency increases from 11.7% to 33.2%. The utilisation of the thermal energy during the mid-heating season could result in the building thermal demands being largely met from the PV system.

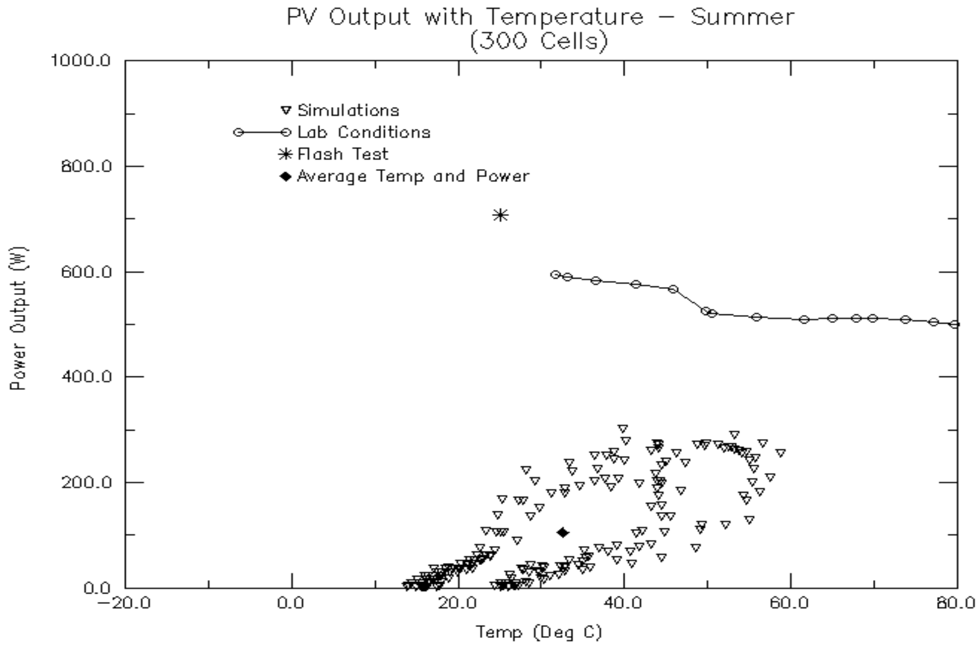

Figure 5: PV panel, seasonal performance.

Further work is now underway in two areas: simulations at the real building scale in order to assess the utilisability of the generated electrical/thermal energy and a replication study to determine PV system performance in other European climates.

	Winter	Week in Spring	Summer
Insolation (kWh)	26.5	132.2	211.6
Electrical Power (kWh)	3.1	16.3	25.8
Electrical Efficiency (%)	11.7	12.3	12.2
Heat Recovered (kWh)	7.3	42.0	94.6
CHP Efficiency (%)	33.2	44.1	56.9
CO_2 Reduction (kg)	4.3	23.9	34.9

Table I: Effective seasonal operating efficiencies.

4. REFERENCES

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