Sustainability-Oriented Innovation of a Multilayered Cement-Based Roof Element

Adriana Angelotti, Sonia Leva, Giulio Zani, and Marco di Prisco

Synopsis: Sustainability of cement-based construction components is becoming a key point of the structural design process, since the implementation of green strategies favors an overall reduction of economic and environmental impacts. In the framework of a regionally funded research project, an innovative multi-layered roof element for the retrofitting of existing industrial buildings was developed at Politecnico di Milano. The development followed a holistic approach focusing on two main levels: 1) the optimization of the transverse section, aimed at minimizing the employment of cementitious composites such as High Performances Fiber Reinforced Concrete (HPFRC) and Textile Reinforced Concrete (TRC) and 2) the improvement of the energy performances, through the selection of adequate insulating materials (polystyrene and glass foam were considered) and the design of Building-Integrated PhotoVoltaics (BIPV). In this paper, preliminary considerations pertaining to the sectional and structural behavior of a 2.5 × 5 m [8.2 × 16.4 ft.] secondary panel are followed by the numerical/experimental evaluation of the thermal transmittance U and the BIPV performances. In this regard, a small demo roofing system housing three full scale panels was monitored throughout two Summer weeks, leading to the assessment of photovoltaics Performance Ratios (PR) and effectiveness of the architectural integration.

Keywords: building-integrated photovoltaics; energy performances; high-performances fiber-reinforced concrete; roof element; sandwich panel; textile-reinforced concrete; thermal transmittance

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INTRODUCTION

After Germany, Italy is the European country counting the larger amount of industrial buildings (about 650.000); since a significant part of them is now obsolete and the 20% of the global stock is located in Lombardy Region, local authorities recently financed a research project in continuity with a national program of incentives aimed at stimulating the replacement of building elements not specifically designed to withstand seismic loads and underperforming in terms of thermo-hygrometric and environmental characteristics. In this framework, Politecnico di Milano, in partnership with a glass textiles producer and a PV installer, developed a secondary roof element for the retrofitting of existing structures. Innovation and sustainability were addressed by upgrading the traditional precast concrete technology, following objectives of dead weight reduction, thermal efficiency, structural robustness, fire safety and effective integration of photovoltaic systems.

The proposed 2.5 × 5 m [8.2 × 16.4 ft.] panel, introduced in **Fig. 1**, is a cement-based multilayered system [1] consisting of a 100 to 200 mm [3.94 to 7.87 in.] thick polystyrene core set within a 20 mm [0.79 in.] thick HPFRCC [2] extrados and a 10 mm [0.39 in.] thick TRC [3] intrados. It is characterized by a self-weight of 120 kg/m^2 [2847.64 lb/ft^2], a thermal transmittance of 0.42 W/(m^2·K) [0.074 BTU/(h·ft^2·°F)], the absence of additional waterproofing layers, a fire resistance greater than 30 minutes and a full integration of PV panels, thanks to the optimized shape of the transverse section (**Fig. 2**). The longitudinal bearing capacity is guaranteed by the presence of Alkali-Resistant glass textiles embedded in the cement-based outer crusts, working in parallel with two Φ 14 mm [~ W 24] ordinary steel bars.

As final outcome of the research project, 10 nominally identical full-scale prototypes were produced in a precast concrete production plant, allowing the assessment of the mechanical and the energy performances. In its initial phase, the campaign comprised 2 longitudinal bending tests [4], 2 transverse bending tests [4], 2 shear tests [5] and 1 test in fire conditions [6]. This paper will mainly focus on the last experimental study, which provided the monitoring of a demo-structure consisting of 3 prototypes housing 12 PV modules.

EXPERIMENTAL INVESTIGATION

The experimental investigation was conducted at three main levels: 1) the material level, which focused on the mechanical and thermal characterization of the cement-based composites, 2) the meso-scale level, in which the cementitious materials were coupled to alternative insulating cores [7] and 3) the abovementioned full-scale level.

Materials

Both the cement-based composites (HPFRCC and TRC) were obtained starting from a reference High Performance Concrete (HPC), optimized according to the precaster procedures (**Table 1**). In case of HPFRCC, 100 kg/m^3 [6.24 lb/ft^3] (1.2% by volume) of straight high-carbon steel microfibers (length 13 mm [0.51 in.], diameter 0.20 mm [0.08 in.], aspect ratio of 65) were added to the fresh-state matrix. According to the Model Code 2010 characterization procedures based on residual flexural strengths, the steel fiber-reinforced composite could be classified as a 14a class material [8, 9]. In case of TRC, one Alkali-Resistant (AR) glass fabric was employed, orienting the warp along the transverse direction of the panel. Further information can be found in [4, 5, 6]. Even though more sustainable insulating materials - as glass foams obtained by recycling processes - were preliminary investigated at the meso-scale [7], the sandwich was completed by an ordinary EPS100 polystyrene core, following economical and mechanical considerations.

In order to evaluate the energy performance of the panel, Transient Plane Source technique (TPS) [10] was used to measure the thermal conductivity of the HPFRCC material. In TPS, a plane source (Hot Disk) inserted between two samples of the material provides a step heat pulse and measures the surface temperature variation with time. The measurements were then performed on 4 cylindrical samples with a diameter of 200 mm [7.87 in.] and a thickness of 30 mm [1.18 in.] (**Fig. 3**). The same procedure was adopted for preparing the samples and no special orientation of the fibers was favored.

By coupling the 4 samples in different ways 14 measurements were performed, leading to an average thermal conductivity $\lambda = 1.91 \pm 0.05$ W/(m·K) [1.10 ± 0.029 BTU/(h·ft·°F)]. Such result is coherent with CIBSE Guide value equal to 1.9 W/(m·K) [1.10 BTU/(h·ft·°F)] referring to a high density reinforced concrete [11], but significantly higher than the value of 0.94 W/(m·K) [0.54 BTU/(h·ft·°F)] reported by Corinaldesi and Moriconi for UHPFRCC [12]. Therefore, given the large range of thermal conductivity values available in literature for analogous materials, the measurements performed allowed to identify with good accuracy the conductivity for the specific HPFRCC adopted in the panel.

Full-scale panels prototyping, testing and monitoring

The full-scale prototypes were produced according to a fresh-state layered procedure comprising the use of two steel formworks, as displayed in **Fig. 4a**. After the demolding and the 28-days curing at ambient conditions, six panels were tested in longitudinal bending (**Fig. 4b**), transverse bending and shear, as previously mentioned. As shown in [4, 5], the panels exhibited remarkable structural capacities in terms of strength, ductility and robustness, despite the small thickness of the employed cement-based composites. In fire conditions, the panel met the minimum requirements of Italian industrial buildings, even though destructive spalling was observed after 30 minutes [6].

The last three prototypes were employed in the erection of a 5 m × 7.5 m [16.4 × 24.6 ft.] demo-structure, hosted within the new Lecco Campus of Politecnico di Milano (**Fig. 5**).

12 photovoltaic modules were installed on the proposed roofing elements, for a total nominal electric power of 2.76 kW. This step of the experimental research had the following objectives:

1. checking on the field the assembly procedures of the photovoltaic modules, supported by an aluminum sub-structure anchored to the cementitious extrados by means of a glued joint;
2. monitoring the energy performances of the integrated photovoltaic modules, with regard to ventilation and surface temperatures;
3. monitoring durability, with particular reference to the waterproof performance.

Concerning objective no. 2, the electricity production of the 12 modules was monitored by means of a SMA monitoring system and SUNNY WEBBOX acquisition system including a meteo station for the solar irradiance measurement. At the same time, the operating thermal conditions of 4 modules in a stripe were monitored, by means of 14 thermocouples and 4 heat flow meters connected to a NI DAQ system. As shown in **Fig. 6** and **Fig. 7**, reporting the position of the thermal probes and of the heat flow meters, the sensors allowed to measure:

- the air temperature at the bottom (inlet) and at the top (outlet) of the 4 modules stripe;
- the air temperature in the air gap below the modules, at the center of each of the 4 modules;
- the temperatures of the surfaces facing the air gap, namely the PV modules back surface and the top panels surface temperatures, at the center of each PV module;
- the heat flow per unit surface exchanged at the back of each PV module.

SIMPLIFIED ANALYSES AND NUMERICAL INVESTIGATIONS

Mechanical performance

The longitudinal bending behavior of the multilayered panel was preliminary assessed by means of analytical models based on a plane-section kinematic assumption. This simplified approach favored the optimization of the transverse section, suggesting the introduction of the two Φ 14 mm [~ W 24] longitudinal steel bars. Consequently, the section was iteratively changed, leading to the configuration displayed in **Fig. 2**. Refined numerical investigations considering the non-linear response of the materials confirmed the preliminary results [4].

Energy performance

The energy performance of the panel was evaluated in terms of thermal transmittance. Given the geometry of the panel section (**Fig. 2**), designed in order to accommodate the PV modules and leave an air gap sufficient for ventilation on their back, the heat flow across the panel is two-dimensional. Therefore, a steady state numerical simulation of the heat transfer was performed by means of the software THERM [13], allowing to derive an equivalent U-value for the panel including thermal bridges effects.

Fig. 8 shows the results for the panel having 100 mm [3.94 in.] of EPS in the central part and 200 mm [7.87 in.] on the sides. The comparison between the top and the bottom of **Fig. 8** shows that excavating the insulation material near the corners of the panel, in order to allow a proper covering of the reinforcement bars, further enhances the thermal bridge through the concrete at the sides. The resulting equivalent U-value is equal to 0.42 W/(m^2·K) [0.074 BTU/(h·ft^2·°F)]. In order to comply with the different energy retrofit requirements for industrial buildings roofs in Lombardy Region, that become more strict as the ratio roofing surface over building heat loss surface increases and as the winter degree days increase, some variants of the panel were designed, by increasing the EPS thicknesses at the center and at the sides, but maintaining a 100 mm [3.94 in.] difference between the two parts. The 100 mm/200 mm [3.94 in./ 7.87 in.], 120 mm/220 mm [4.72 in./ 8.66 in.], 150 mm/250 mm [5.91 in./ 9.84 in.] and 200 mm/300 mm [7.87 in./ 11.81 in.] configurations resulted in U-values 0.42 W/(m^2·K) [0.074 BTU/(h·ft^2·°F)], 0.37 W/(m^2·K) [0.065 BTU/(h·ft^2·°F)], 0.31 W/(m^2·K) [0.055 BTU/(h·ft^2·°F)] and 0.25 W/(m^2·K) [0.044 BTU/(h·ft^2·°F)] respectively.

EXPERIMENTAL RESULTS AND DISCUSSION

Electrical and thermal measurements on the demo roofing system were carried out for a period of two weeks between June and July 2015, in order to verify energy production and overheating under high solar irradiation and high ambient temperature conditions.

Electricity production was evaluated in terms of Performance Ratio (PR), calculated from measured quantities. PR is the ratio between the net electricity production from the overall PV system and the theoretical energy input [14]. A daily basis was adopted in this case to calculate the PR. Over the monitored period, the average PR was assessed to be 71.6%, allowing to classify the plant performance as very good/excellent, taking into account the following issues:

- the very small size of the demo plant;
- the increase in the number and length of the cables, with respect to a typical installation, in order to measure the electricity production of each module individually; this resulted in an estimated penalty of the PR of about 3%;
- the working temperature of the modules, higher than 40°C [104°F]; this resulted in an estimated penalty of the PR of about 5%;
- the building integration configuration.

The impact of the building integration was investigated by analyzing temperature and heat flow results on the PV modules and the relative air gap on the back.

Fig. 9 and **Fig. 10** show the time profiles during one week of the back module temperature (PV3), the air gap temperature (TA3), the panel surface temperature (TB3), the ambient air temperature (TAEXT) and the thermal flux density (TF3) for PV3 module (**Fig. 6**). The module back temperature maxima reached 65-70°C [149-158°F], while ambient air temperature reached up to 32°C [89.6°F]. The module dissipates heat by convection with the air in the gap and by radiation towards the roof surface. The maximum heat flux density is about 350 W/m^2 [111.02 BTU/(ft^2h)].

The daily PR can thus be correlated with the thermal conditions of the modules, summarized by the daily average modules back temperature. **Fig. 11** actually shows that the higher the module back temperature, the lower the PR namely the electricity production performance. However, the range of backside temperatures of the PV modules measured during the campaign is comparable with experimental data from literature [15] referring to PV modules with a standard mounting on the roof by means of metallic racks. Therefore, it can be concluded that the PV modules integration into the roofing panels is able to ensure the necessary heat dissipation by natural ventilation.

CONCLUSIONS

Based on the results of this experimental investigation, the following conclusions are drawn:

1. high performance cement-based materials represent an interesting solution for the development of innovative building components, since they guarantee at the same time significant bearing capacities and reduction of dead weights;
2. sustainability of concrete structures can be maximized through the employment of integrated design approaches, which allow the simultaneous fulfillment of architectural, structural and energy requirements;

3. the integrated design approach can successfully include active energy components such as PV panels; the experimental testing of the prototype panel proved that architectural integration does not compromise the necessary cooling of the panels by natural ventilation, resulting in a very good electricity production performance;
4. given the mechanical and energy performances of the proposed panel, it can be concluded that this technology can be promisingly adopted in the retrofitting and upgrading of existing industrial buildings that no longer meet the requirements imposed by national regulations.

ACKNOWLEDGMENTS

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TABLES AND FIGURES

Table 1–HPC mix design

Component	Dosage, kg/m^3 (lb/ft^3)
Cement I 52.5	600 (37.45)
Sand 0÷2 mm (No. 10)	847 (52.87)
Water	225 (14.04)
Superplasticizer	28 (1.75)
Blast furnace slag	500 (31.21)

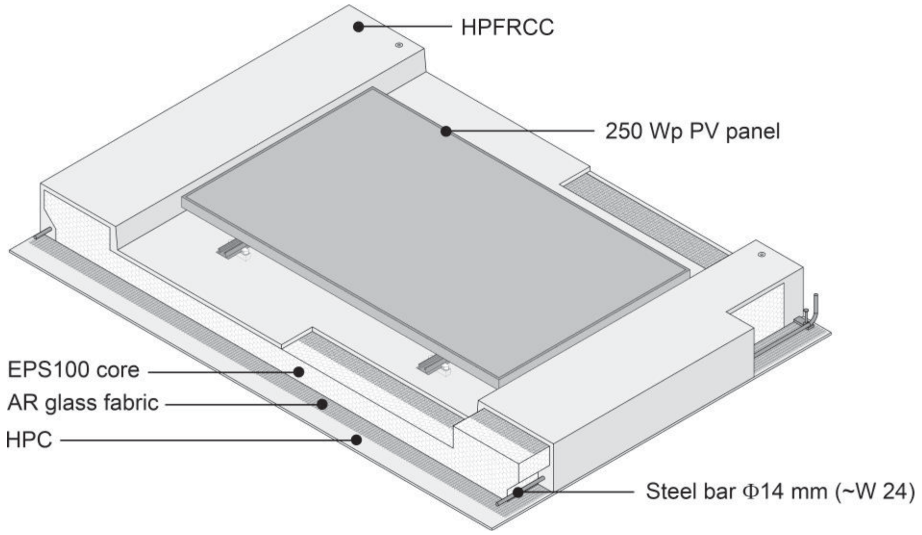


Fig. 1–The proposed multilayered roofing panel: three-dimensional view

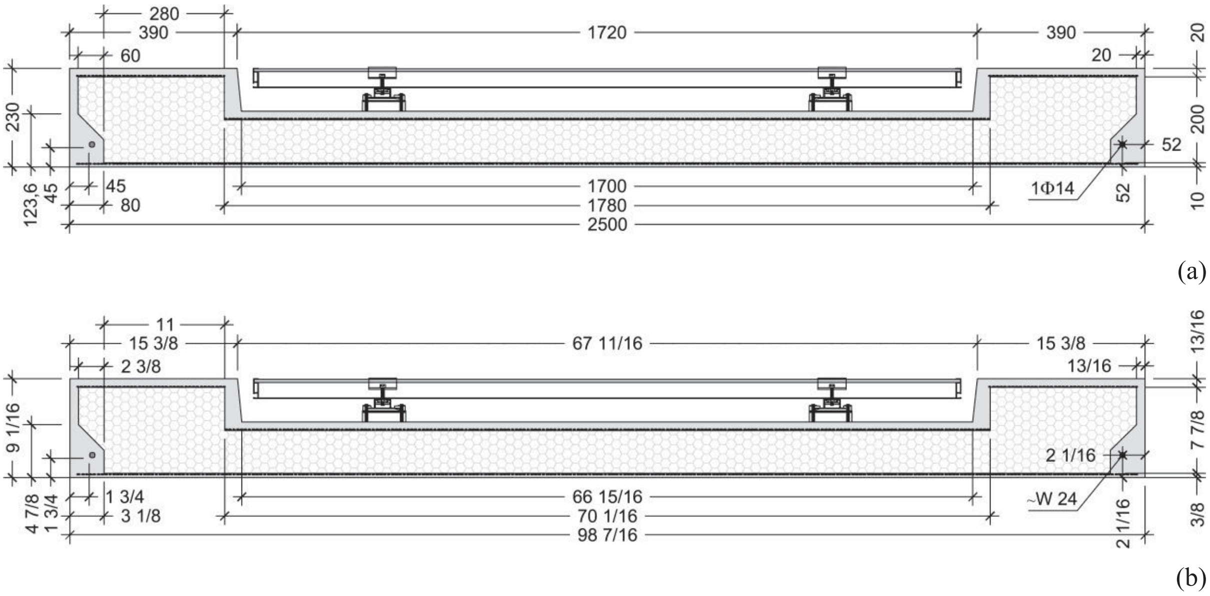


Fig. 2–The proposed multilayered roofing panel: transverse section, with dimensions expressed in mm (a) and inches (b)

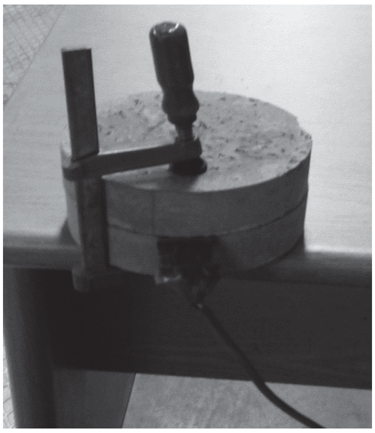


Fig. 3–Thermal conductivity measurement of the HPFRCC samples by means of TPS apparatus

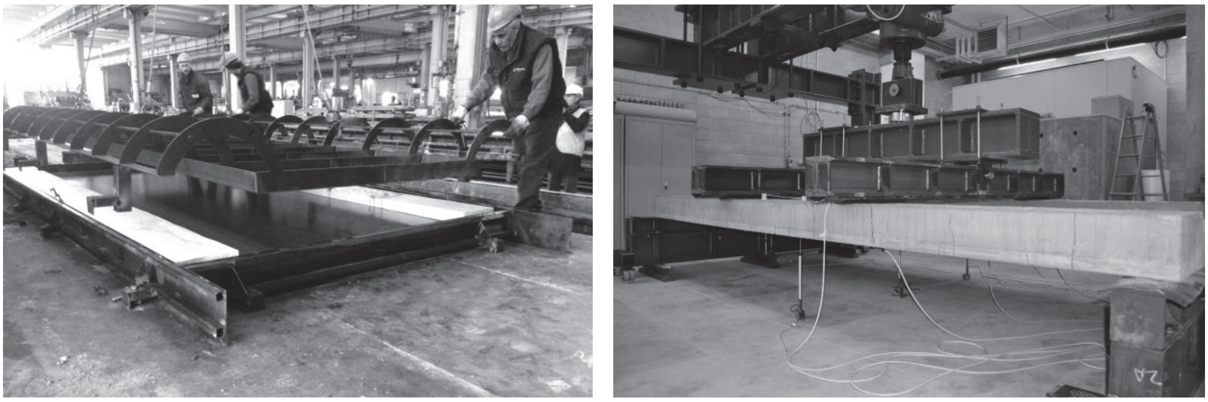

(a) (b)

Fig. 4–Full-scale panel production (a) and mechanical testing (b)

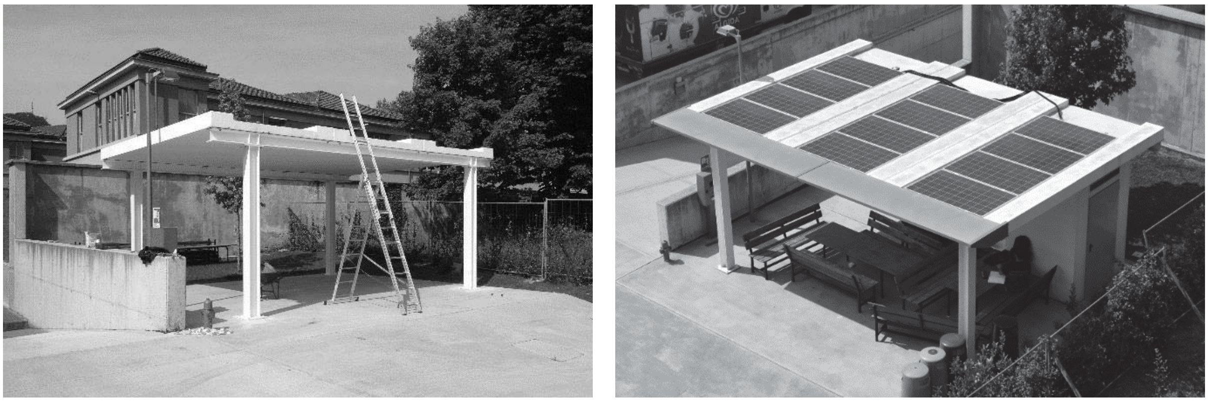

(a) (b)

Fig. 5–Demo structure: front view (a) and top view of the installed PV modules (b)

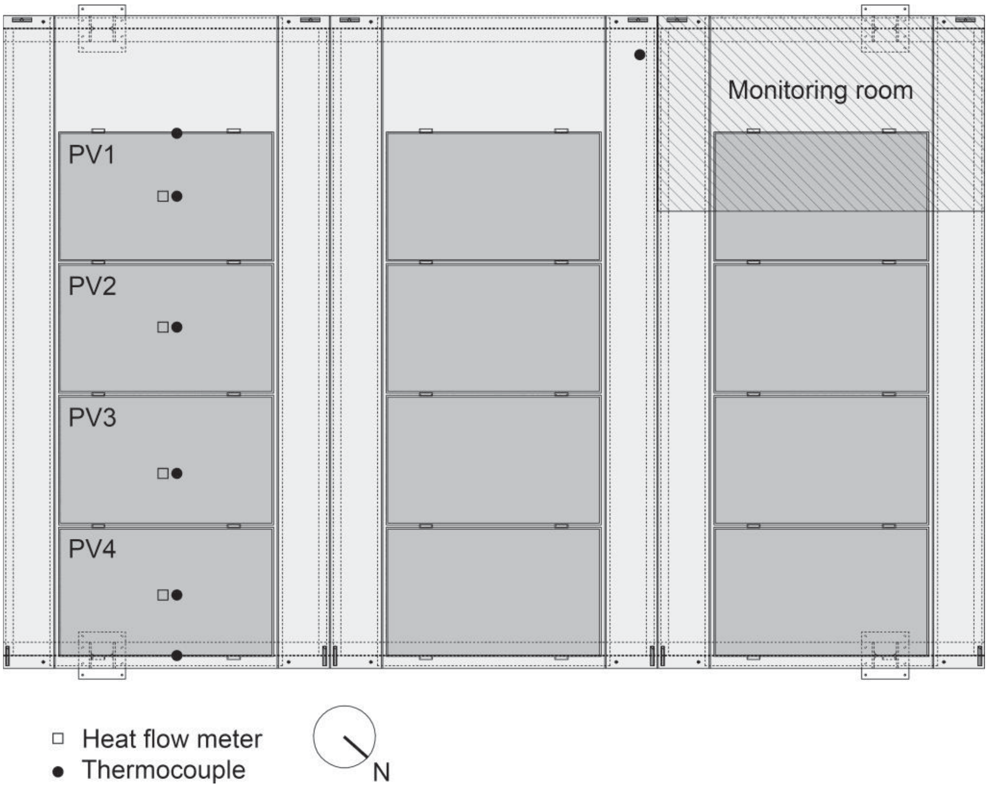


Fig. 6–Layout of the demo roofing system, showing the heat flow meters and the temperature probes position on PV panels 1-4

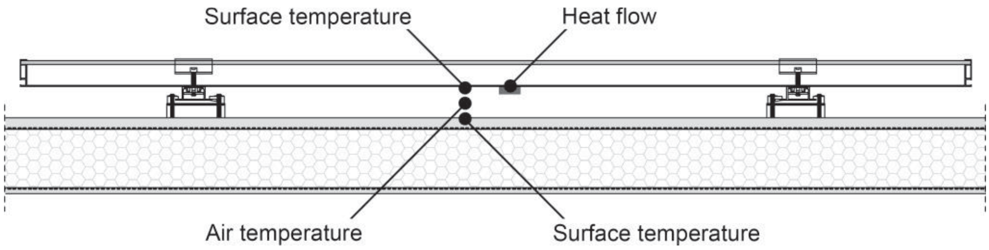
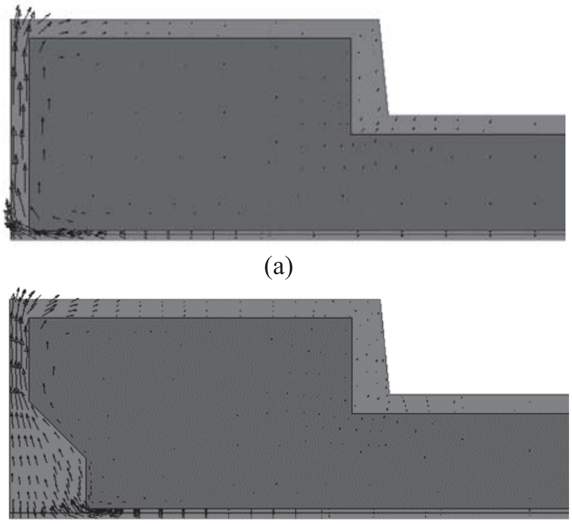


Fig. 7–Side view of each monitored PV panel, showing the position of the surfaces temperature probes, the air temperature probe and of the heat flow meter



(a)

(b)

Fig. 8–Numerical simulations showing the heat flow vectors across the base panel section (a) and the modified section (b), where the insulation material in the corner is excavated

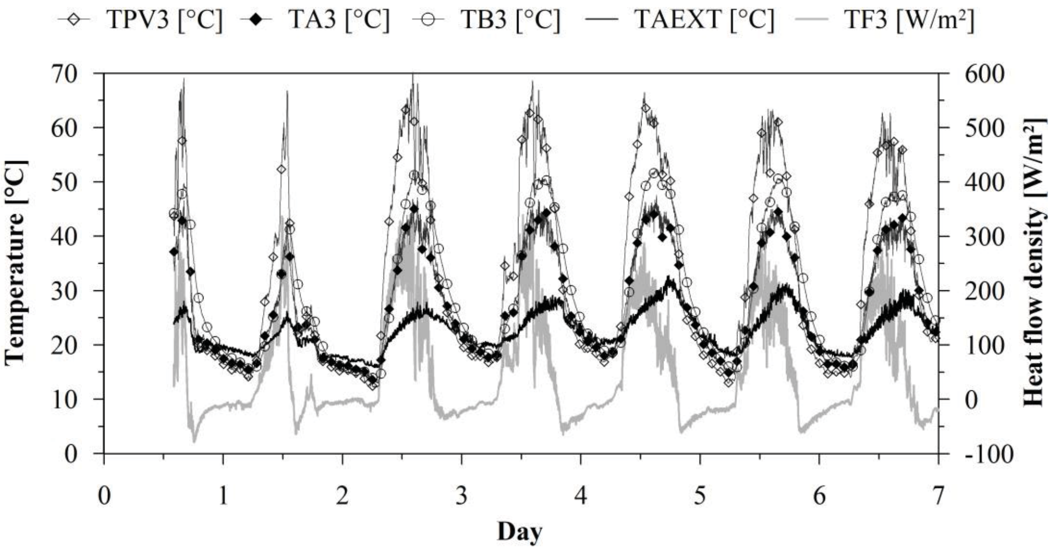


Fig. 9–Temperatures and heat flow density on PV3 module during a week in June/July 2015 (metric units)

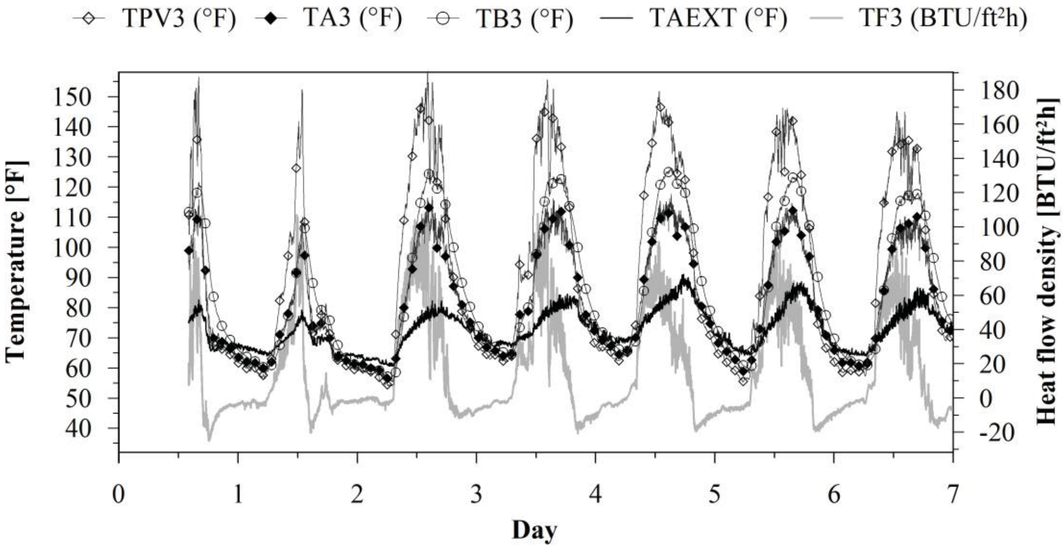


Fig. 10–Temperatures and heat flow density on PV3 module during a week in June/July 2015 (imperial units)

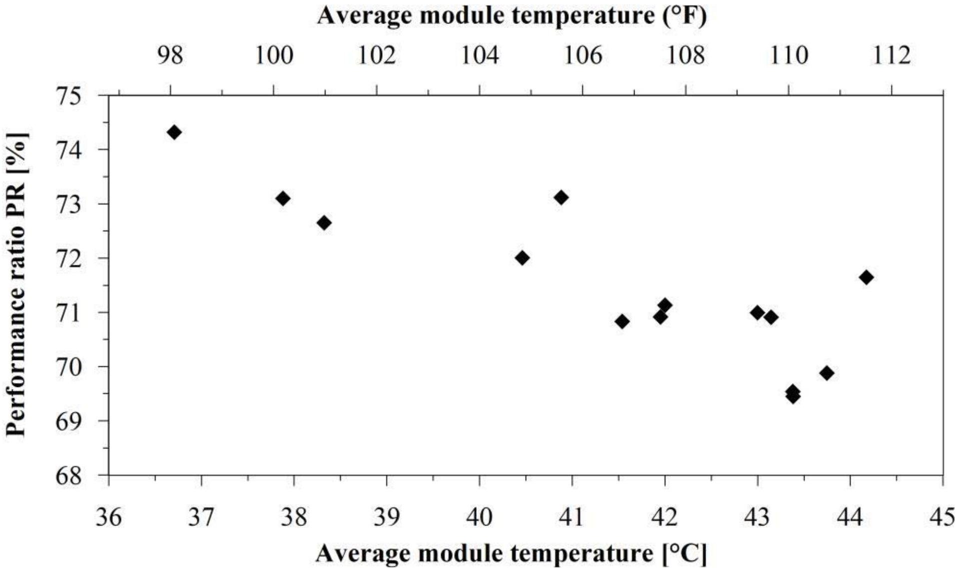


Fig. 11–Daily PR as a function of the daily average backside temperature of the PV modules during monitoring period in June/July 2015