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Study of a building integrated bifacial photovoltaic facade

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Summary: An increase of knowledge of the mid- term performance of building integrated bifacial photovoltaic modules in real conditions is required in order to validate their relevance. Thus, in this work, the experimental study during more than one year of an innovative building integrated bifacial photovoltaic ventilated façade developed in the framework of the CONIPHER Life project and mounted on a test cell at Le Bourget du Lac is presented focusing mainly on the photovoltaic modules thermal behaviour and electrical performance. Moreover, a specific attention is made on the photovoltaic façade seasonal impact on the building energy consumption compared to a similar test cell comprising a non-insulated concrete wall. An important thermal gradient is observed along the façade in warm season, as expected, mainly due to site albedo, with mean photovoltaic modules temperature up to 68.3°C. The innovative facade produced an annual cumulated electrical energy of 63.8 kWh/m² with a performance ratio of 0.7 and a mean annual efficiency of 6.3%. A huge reduction of the building total energy consumption up to 92% in winter compared to reference is observed. As further studies, the facade will be installed on an office building in order to demonstrate its performance in real conditions.

Keywords

Building Integrated Photovoltaic (BIPV); bifacial PV modules, experimentation; building total energy performance; concrete facade.

1. Introduction

Considering its whole life cycle, building sector is responsible for 40% of total European energy consumption and 36% of greenhouse gas emissions. The renovation of 3% of existing buildings is, thus, encouraged. In this sense, in accordance with the European energy policies of 2010, the construction of Nearly Zero-Energy Buildings integrating renewable energy sources such as solar photovoltaics is essential for a total or major coverage of energy needs (EU, 2020). Indeed, the building envelope is a critical element since it influences the indoor thermal loads but it also represents a large available area for energy production, especially facades.

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42 However, in the case of facade integrated photovoltaic installations, a decrease of electrical
43 performance is observed compared to rack-mounted or rooftop photovoltaic systems mainly due to the
44 higher risk of shading and to the less advantageous solar incident angle (Vulkan et al., 2018) in
45 addition to the expected modules overheating and the important thermal gradient from top to bottom of
46 the facade (Freitas and Brito, 2019). Moreover, in urban area, these more visible systems have to
47 comply with the public, market, architects and regulatory requirements concerning aesthetics and
48 performance more than rooftop installations (Attoye et al., 2017), thus the development of innovative
49 and aesthetical photovoltaic prototypes for facade integration with improved performance is
50 necessary, especially for building deep renovation (Saretta et al., 2019; Shukla et al., 2017; Freitas
51 and Brito, 2019). Various configurations of building integrated façades can be found in the literature
52 including different photovoltaic modules technologies (opaque or semi-transparent, crystalline silicon
53 or thin film) but, only few projects include bifacial photovoltaic modules although the additional
54 electricity production at their backside (Gu et al., 2020), leading to the lack of knowledge on their
55 performance in real conditions and so, to the slow development of their application in the building
56 sector. Thus, numerical and experimental studies in situ and on at least one year are necessary to
57 validate the relevance of this technology for a building integration.

58 According to the state of art, photovoltaic modules are applied in four main kinds of facade
59 elements, namely, solar glazed facades, sun-shading elements, ventilated facades (with an air gap at
60 the rear side of photovoltaic modules) and non-ventilated facades (photovoltaic modules directly in
61 contact with the facade). For a satisfactory rear side production, the use of bifacial photovoltaic
62 modules requires the installation of a reflective layer located at an optimal distance and reflecting solar
63 radiation towards their backside (Chen et al., 2021; Soria et al., 2015; Ko et al., 2021; Kim et al., 2021;
64 Muehleisen et al., 2021), which is mainly possible with ventilated façades. Nevertheless, for an
65 integration into non-ventilated facades, since the bifacial photovoltaic modules have a semi-
66 transparent structure, the reflective layer could be mounted directly in contact with their rear glass in
67 order to exploit its optical properties (reflection coefficient of the glass layer). Moreover, the reflection
68 properties of the coating of a room internal walls (ceiling, walls and floor) could be adapted in the case
69 of solar glazed facades (Chen et al., 2021).

70 Only few research studies on photovoltaic facades including bifacial technologies could be found in
71 literature. In 2015, Soria et al. analysed numerically and experimentally on short periods the relevance
72 of the integration of a semi-transparent bifacial technology to a ventilated facade from the electrical
73 and optical points of view and considering various innovative module architectures, air gap
74 thicknesses and reflective layer materials. They obtained numerically an annual electrical energy gain
75 of nearly 25% on a small scale test bench compared to a standard photovoltaic module (Soria et al.,
76 2015). Then, in 2020, Tina et al. compared numerically the daily thermal behaviour and electrical
77 performance of four non-insulated building integrated photovoltaic facades and their heat exchange
78 with the building envelope. The systems considered in their study were differentiated by the presence
79 of an air gap, by the reflective surface material (standard wall plaster or highly reflective paint with
80 reflective coefficients of, respectively 0.2 and 0.7) and by the photovoltaic technology (standard or

81 bifacial modules). They explained that the use of bifacial modules, even with the plaster coating as
82 reflective layer, permitted an increase of the electrical power produced in peak hours of 2.9%
83 compared to the monofacial photovoltaic ventilated façade and of 4.4% compared to the non-
84 ventilated one. Moreover, the use of the reflective paint led to an additional increase of production of
85 nearly 2.9% (Tina et al., 2020).

86 These studies present interesting parametric studies permitting to estimate the impact of the
87 bifacial system operating conditions on its performance. Nevertheless, experimental studies are
88 realized on reduced scale facade installations, on short periods (hours, days, weeks, months) and
89 annual data are obtained only through simulation, which is not sufficient to validate the relevance of
90 this technology especially with industrial and financing partners. (Tina et al., 2020; Soria et al., 2015;
91 Chen et al., 2021)

92 In this sense, in this work, the experimental study of an innovative configuration of building
93 integrated glass-glass bifacial photovoltaic ventilated facade is presented focusing mainly on the
94 thermal behaviour and the electrical performance of the photovoltaic modules, which has not been
95 proposed previously on an annual base and at full scale. In addition, a specific attention is made on
96 the whole facade solution comprising the bifacial photovoltaic modules, their rear side reflective
97 concrete panels and the facade insulation layer through the evaluation of its seasonal contribution to
98 reduce a building total energy consumption compared to a standard non-insulated concrete wall.
99 Indeed, the various studies existing on this aspect highlight that a ventilated photovoltaic facade
100 configuration contributes to reduce the cooling load in summer while a non- ventilated system has a
101 positive impact on heating load in winter, when it is well designed (Yu et al., 2021; Tina et al., 2020; Li
102 et al., 2019; Han et al., 2019; Wang et al., 2017). More precisely, Peng et al. showed numerically that
103 compared to a standard concrete wall, a solar double skin photovoltaic wall could permit a reduction of
104 heat gain by 51% in summer and of heat loss by 32% in winter (Peng et al., 2013). Then, in 2019, Li et
105 al. modelled and tested a non- ventilated precast concrete photovoltaic facade for high-rise buildings
106 permitting a heating load saving of 19.67 kWh/m²/year (corresponding to a relative difference of nearly
107 56.7%) and an increase of cooling load of 14.70 kWh/m²/year compared to a concrete wall (Li et al.,
108 2019).

109 In this paper, the design of the innovative bifacial photovoltaic facade element is first presented.
110 Then, the outdoor tests performed on two full scale test cells at Le Bourget du Lac integrating the
111 south-oriented facade studied and a reference non-insulated concrete wall in order to measure
112 thermal, electrical, energy consumption and weather data during more than one year are described.
113 The temperature and electrical production of the photovoltaic modules are analysed on daily, monthly
114 and annual bases. Moreover, in order to estimate the impact of the system on heat transfers through
115 the integration facade, the temperature distributions along the two facades are compared using
116 thermal images. Finally, a comparison of the tests cells total energy consumption for heating and
117 cooling is proposed considering the cold and the warm periods.

118

119

120 **2. Description of the BIPV facade element designed**

121

122 The innovative bifacial photovoltaic (PV) facade element studied was designed in the framework of
123 the CONIPHER Life project mainly in order to encourage deep energy renovation of building facades.
124 Its configuration aims mainly to ensure a reduction of energy consumption for heating of at least 60%
125 compared to standard non-insulated concrete wall through a sealed fastening solution for an easy and
126 fast installation and dismounting of the bifacial PV modules and a whole facade high thermal
127 resistance of nearly 5 m².K/W.

128 The prototype configuration was thus developed in order to solve some expected issues such as
129 the thermal bridges within the insulation layer due to fastening nuts and the reduced level of cooling of
130 building integrated PV modules backside.

131 The photovoltaic facade basic element of 0.9 m long and 0.83 m wide is composed of a nearly 57
132 Wp bifacial glass-glass photovoltaic module (see figure 1 a and figure 1 b) comprising a 2 cm thick
133 fully open air gap and an insulated ultra-high performance fiber concrete panel of Vicat company at
134 the rear side. It is fixed on the initial concrete wall of the test cell using four fastening nuts (see figure 2
135 a, figure 2 b and figure 2 c). The fastening profiles combined with thermal breaking plastic caps and
136 expansion joints were specifically designed by ARaymond company for the project considering also
137 seismic risks (see figure 2 a and figure 2 b).

138 Eight PV basic elements were mounted in an open joint ventilated facade configuration
139 (Agathokleous and Kalogirou, 2016; Sanjuan et al., 2011a) leading to air entering or exiting the
140 discontinuous air gap at different levels between the PV modules. According to the BIPV facade layout
141 (in two columns of four PV modules), outdoor air will tend to enter in the air gap at the bottom and the
142 top of the first row of PV modules and to exit at the bottom and top of the upper row of PV modules.
143 (See figure 2 c)

144 The eight integrated octagonal semi-transparent bifacial PV modules were manufactured by CEA.
145 Each module of 0.854 m long and 0.763 m wide (with a 45° chamfer of glass layers reducing the PV
146 module length and width of 81 mm) is composed of a 3 mm thick tempered front glass, a 600 μm
147 ethylene vinyl acetate (EVA) front layer, 24 monocrystalline silicon heterojunction (HET) bifacial half-
148 cells in series (set out in 6 columns and 4 rows), a 600 μm EVA back layer and a 3 mm thick tempered
149 back glass. The transparency rate of each PV module was of nearly 61.6%. The half- cells were
150 obtained by cutting 15.6 cm x 15.6 cm PV cells with a method patented by CEA (CEA, 2017). The
151 weight of the PV module is of nearly 10.2 kg. The use of half-cells permitted to increase the PV
152 module voltage without modifying its size for a compatibility with standard inverter technologies (Soria
153 et al., 2015). (See figure 1)

154 Since the reflective coefficient values of a concrete material are comprised between nearly 0.25
155 and 0.30 over the visible spectrum (from 380 nm to 780 nm) (Jensen, 2007; Raybaud et al., 2019), the
156 smooth surface of the 2 cm thick fiber concrete panels was used as reflective layer without specific
157 treatment, as first hypothesis. Figure 2 c summarizes the working principle of the solar bifacial facade
158 studied including the expected air flow direction in the air gap and the main solar radiation
159 transmission through its different layers. More precisely, the solar radiation that reaches directly the
160 front side of PV cells is partly absorbed (by the front glass layer on the corresponding areas and the
161 PV cells) and partly reflected towards environment. The solar radiation reaching the semi-transparent

162 areas of PV modules is partly reflected, absorbed and transferred by their glass layers. The
 163 transferred part of the solar radiation is partly absorbed by the insulated fiber concrete panels and
 164 reflected towards the rear face of PV modules (and thus, of PV cells) for an additional electrical power
 165 production. The solar radiation reaching directly the fiber concrete panels and their interfaces is partly
 166 absorbed and partly reflected towards the rear face of PV cells and environment (see figure 2 c). It is
 167 to be noted that existing multiple absorption, transmission and reflection of solar radiation in the air
 168 gap and within the PV modules are not represented in figure 2 c.

169 Finally, for the choice of the insulation layer material, in order to reach the expected facade thermal
 170 properties, a comparison of different insulation products (phenolic foam, glass fiber wool, rock wool
 171 and foamed glass) was performed considering their environmental impact, their physical properties
 172 and their costs. Table 1 presents the main results obtained based on the insulation materials
 173 environmental product declarations (EPD, 2021) and considering 1 m² of panel with a facade thermal
 174 resistance of 5 m².K/W (value defined based on requirements for facades of the French thermal
 175 regulation RT2012) (ADEME, 2021).

176 The phenolic foam has the lowest thermal conductivity (of 0.021 W/m.K) permitting to obtain the
 177 required thermal resistance with a reduced thickness compared to other insulation materials.
 178 Moreover, for 1 m² of insulation layer, the phenolic foam panel is the lightest (with 3.5 kg) but is more
 179 expensive (with 55 Euros/m²) than the rock wool panel and the glass wool panel (with respectively, 22
 180 Euros/m² and 20 Euros/m²). The glass wool panel seems competitive because of its low weight (of
 181 4.32 kg) and cost, but its reduced rigidity (density of 27 kg/m³) increases risks of packing and thus,
 182 risks of early degradation of the complete solar element. The rock wool panel has a limited weight (of
 183 11.55 kg) and is more rigid than glass wool panel (with a density of 70 kg/m³) to limit risks of packing.
 184 The foamed glass is the densest (with 120 kg/m³) but it is the heaviest (with 24 kg) and the most
 185 expensive (with 240 Euros/m²). Moreover, its energetic footprint is in most cases, the highest, taking
 186 into account environmental impact (for example, with 32.4 kg CO₂-eq. of global warming potential),
 187 waste generation (with 25.2 kg of non-hazardous waste disposed) and resource use (with 497.7 MJ of
 188 total use of non-renewable primary energy resources). (See table 1)

189

190 *Table 1: Comparison of physical properties, costs and environmental impacts (based on their environmental*
 191 *product declarations) of 1 m² of the insulation products considered (phenolic foam, glass fiber wool, rock wool and*
 192 *foamed glass) providing a facade thermal resistance of 5 m².K/W:*

	Phenolic foam	Rock Wool	Foamed Glass	Glass wool
Cost (Euros/m ²)	55	22	240	20
Weight (kg)	3.50	11.55	24	4.32
Density (kg/m ³)	35	70	120	27
Thickness (cm)	10	16.5	20	16
Thermal conductivity (W/m.K)	0.021	0.033	0.040	0.032
Lifetime (year)	50	50	50	50

Environmental impact

Global warming potential (kg CO ₂ -eq)	9.9	13.2	32.4	5.12
Acidification potential of land and water (kg SO ₂ -eq)	0.024	0.107	0.072	0.0304
Eutrophication potential (kg (PO ₄) ₃ -eq)	0.00497	0.00751	0.00904	0.00480
Formation potential of tropospheric ozone photochemical oxidants (kg C ₂ H ₄ -eq)	0.00990	0.00619	0.00481	0.00448
Abiotic depletion potential for non-fossil resources (kg Sb-eq)	0.0000185	0.000000536	0.000169	0.00000176
Resource use				
Total use of renewable primary energy resources (MJ)	4.2	10.7	216.2	13.0
Total use of non-renewable primary energy resources (MJ)	292.4	174.9	497.7	144.0
Waste				
Non-hazardous waste disposed (kg)	5.1	14.0	25.2	6.4
Radioactive waste disposed (kg)	0.00171	0.000446	0.00537	0.000544

193

194 With a high fire resistance, a sufficient density and a competitive cost, a 20 cm thick rock wool
 195 insulation layer (of 0.033 W/m.K of thermal conductivity) was selected as a good compromise for the
 196 studied prototype. Moreover, it is fully recyclable and has a reduced energy footprint compared to the
 197 other insulation materials considered, with 13.2 kg CO₂-eq. of global warming potential, 0.107 kg
 198 SO₂-eq of acidification potential of land and water, 0.00751 kg (PO₄)₃-eq of eutrophication potential,
 199 0.00619 kg C₂H₄-eq of formation potential of tropospheric ozone photochemical oxidants,
 200 0.000000536 kg Sb-eq of abiotic depletion potential for non-fossil resources, 10.7 MJ of total use of
 201 renewable primary energy resources, 174.9 MJ of total use of non-renewable primary energy
 202 resources, 14 kg of non-hazardous waste disposed and 0.000446 kg of radioactive waste disposed.
 203 (See table 1)

204



(a)



(b)

Figure 1: CONIPHER Heterojunction bifacial photovoltaic module (a: front side; b: backside)

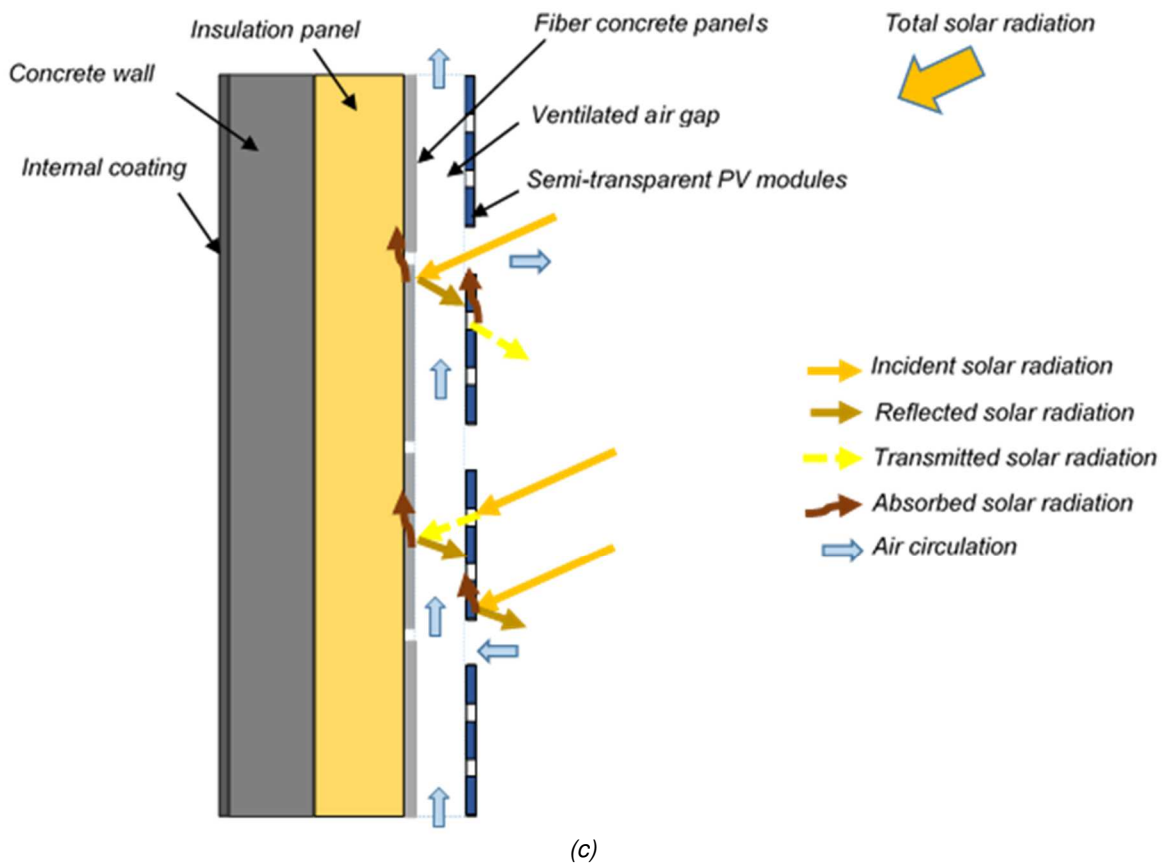
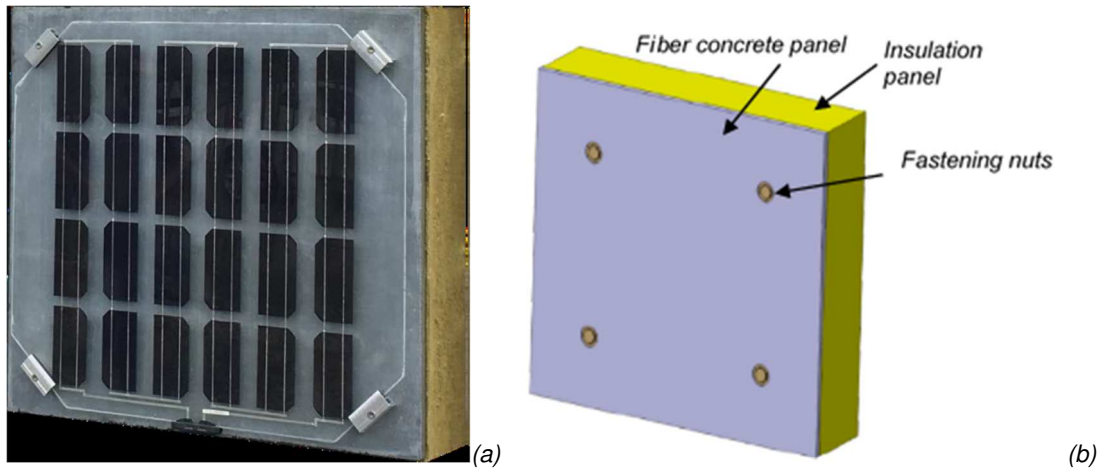
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214 *Figure 2: Schemes of the insulated fiber concrete panel (a) and photograph (b) of the CONIPHER BIPV panel and*
215 *working principle on the solar facade vertical section considering expected air flow direction in the air gap and*
216 *main solar radiation transmissions (with PV cells on blue zones and semi-transparent areas on white zones of PV*
217 *modules) (c)*

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219
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221
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223

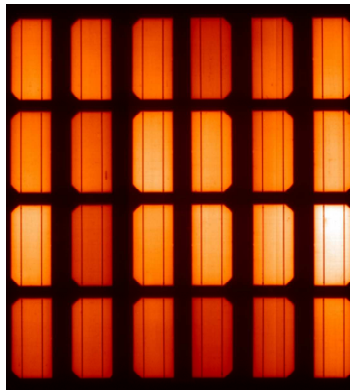
Prior to the tests campaign, flash-tests and electroluminescence tests have been performed on the eight PV modules under standard test conditions (or STC, corresponding to a solar radiation of 1000 W/m², a PV cell temperature of 25°C and an air mass of 1.5) considering only their front side in order to obtain their electrical characteristics (see table 2 and figure 3 a), although the bifaciality.

224 Table 2: Electrical characteristics of the eight bifacial PV modules measured with flash-tests: minimum, maximum
225 and mean values of results obtained.

Characteristics	Summary of performance measured			
	Mean	Max	Min	Variance
Open circuit voltage Voc (V)	17.02	17.17	16.91	0.42%
Short-circuit current Isc (A)	4.60	4.65	4.55	0.63%
Nominal electrical power Pmax (Wp)	57.41	58.28	56.71	0.88%
Cell efficiency (%)	20.02	20.32	19.78	0.88%
Fill Factor (%)	73.29	74.80	72.48	0.98%

226
227 Table 2 shows that the eight selected bifacial PV modules have a mean power output of nearly 57
228 Wp with less than 1% of variance. Their mean electrical open-circuit voltage and mean short-circuit
229 current are respectively of nearly 17 V and 4.6 A, with a mean cell efficiency of nearly 20%. The PV
230 modules efficiency is of nearly 8.7%.

231



232
233 Figure 3: Electroluminescence image of a bifacial PV module.

234
235 Figure 3 presents an example of electroluminescence image of a bifacial PV module showing no
236 sign of cells crack.

237
238 Then, the thermal behavior and electrical performance of the developed photovoltaic system was
239 evaluated experimentally in situ during nearly one year.

240

241

242 3. Description of the experimental setup

243

244 The innovative system was integrated on the south-oriented facade of a test cell of the FACT
245 facility (FACade Tool) at CEA site and instrumented. A test campaign was performed from December
246 2018 to December 2019 in order to estimate the thermal behavior and the electrical production of the
247 photovoltaic facade and the test cell energy consumption for heating and cooling. A concrete wall was
248 also mounted and instrumented on a similar test cell used as reference.

249

250

251 3.1. Presentation of the test cells instrumentation

252

253 FACT tool is located at CEA site at Le Bourget du Lac (45° 38' 44" N, 5° 51' 33" E) and is a two-
254 storey modular test building dedicated to envelope components tests and comprising ten cells (of 2.3
255 m of width, 3.9 m of length and 3.3 m of height) (See figure 3 a). The installation site climate is
256 characterized by warm and dry summers and mild winters with monthly mean ambient temperatures
257 comprised between 1.6°C in January and 20.4°C in July.

258

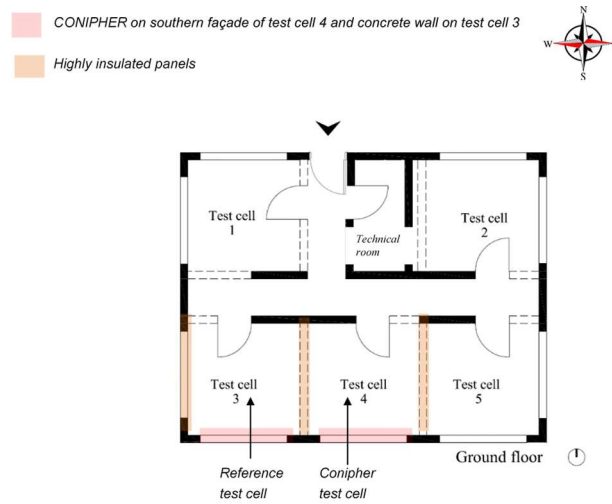


261 *Figure 4: Photographs of FACT tool (a), of the south -oriented reference wall (on the left side) and of CONIPHER*
262 *project BIPV wall (on the right side) (b) at CEA site (at Le Bourget du Lac)*

263

264 Figure 4 b presents a photograph of the south- oriented facades of the two test cells considered for
265 this study and which are 2.3 m wide and 3.3 m high. On the right side of figure 4 b, the 20 cm thick
266 non-insulated cast concrete façade of a test cell (noted test cell 4) comprised the eight bifacial
267 photovoltaic basic elements connected in series to an Enphase M215 micro-inverter located in the
268 room. On the left side, the second test cell (noted test cell 3) was used as reference and comprised a
269 20 cm thick non- insulated cast concrete wall. A similar internal plaster coating was added on both
270 facades. All other facades of the two test cells were highly insulated in order to reduce solar gains and
271 heat transfers with environment (with outdoor ambient air temperature and sky temperature) and with
272 adjacent cells (see figure 5 a).

273



274

(a)



275

276
277

Figure 5: Location of the test cell 3 and the test cell 4 on a plan of FACT tool ground floor (a) and dual-flow air handling unit (CIAT) (b)

278

279 The indoor air setpoint temperature in the two tests cell was fixed with a CLIMACIAT AIRTECH 25
280 dual-flow air handling unit from CIAT at nearly 21°C in cold season and at nearly 26°C in warm season
281 (see figure 5 b).

282 A suitable similar instrumentation was defined for the two test cells for comparison, in order to
283 obtain weather, thermal, electrical and energy consumption data. (See figure 6 and figure 7)

284 More precisely, in the test cell 4, T-type thermocouples were stuck with aluminum tapes at various
285 locations of the wall: on the PV modules 3 and 5 front glass layer avoiding shadings on PV cells, at the
286 interfaces of the facade layers at the level of each PV module, on the internal coating at the level of
287 each PV module and of the interfaces between PV modules 3 and 5 and PV modules 4 and 6 in order
288 to identify possible thermal bridges and then, on the fiber concrete panels of the PV modules 3, 4, 5
289 and 6 (see figure 6 a, figure 6 b and figure 6 c). It is to be noted that for technical constraints related to
290 thermocouples cables passage at the interface around the concrete wall, the number of sensors to be
291 installed directly on the PV modules had to be limited. Thus, supposing the studied system vertical
292 symmetry and the air flow distribution in an open joint ventilated façade (flow entering at the top and
293 the bottom of the lower PV modules and leaving the air gap at the top and the bottom of the upper

294 ones (Sanjuan et al., 2011a)) (see figure 2 c), only half of the south- oriented PV field was
295 instrumented and more precisely, the PV modules close to its center (PV module 3 and PV module 5,
296 here), in order to obtain a relevant mean system temperature.

297 In the test cell 3, thermocouples were stuck on both sides of the cast concrete wall at the right side
298 (see figure 6 d).

299 In both test cells, a T-type thermocouple and a flux meter (Hukseflux of Campbell scientific) were
300 stuck on each wall. Two additional flux meters were mounted on the internal coating of the test cell 4
301 at the level of PV modules 3 and of its interface with PV module 4 (area without PV module) (see
302 figure 6 a and figure 7). A flux meter was also added at the interface between the insulation layer and
303 the concrete wall at the level of PV module 3 in order to analyze more precisely the heat flux
304 distribution within the facade (see figure 6 b).

305 Moreover, a thermal camera was used to observe temperature distribution on the two facades.
306 Measurements of indoor ambient air temperature were realized with thermocouples located at 1 m, 2
307 m and 3 m from the floor level. An anemometer (of Delta Ohms) permitted to measure air velocity in
308 each test cell and, in order to reduce stratification, a fan was activated to mix air.

309 Electrical values (power, voltage and current) after inverter were provided by the micro-inverter
310 connected to a communication gateway using an in-house monitoring program developed in Labview
311 NI software.

312 A weather station existing on CEA site closed to FACT tool permitted to obtain the outdoor ambient
313 air temperature with a sheltered PT100 sensor, the total horizontal solar radiation with a pyranometer
314 in the horizontal plane and the wind velocity and direction with a Windsonic anemometer. An additional
315 pyranometer on the south- oriented facade of FACT tool provided the total solar radiation in the
316 vertical plane (in the PV modules plane).

317 Two thermal energy meters were used to measure the thermal power (with positive values
318 corresponding to heating periods) permitting then, to calculate the energy consumption for heating and
319 cooling in the two test cells (by numerical integration on a defined period of the thermal power
320 measured on each time step in hour).

321 All sensors were connected to a local Agilent datalogger and measured data with a 1 min time step
322 were stored on a CEA common database. Uncertainties of sensors are presented in table 3.

323

324 *Table 3: Uncertainties of the measurement sensors*

Sensors	Uncertainty and sensitivity
T-type thermocouple of TC SA	Less or equal to 2%;
CS215 perforated PT100 probe of Campbell Scientific	$\pm 0.3^{\circ}\text{C}$ at 25°C ; $\pm 0.4^{\circ}\text{C}$ (between $+5$ and $+40^{\circ}\text{C}$); $\pm 0.9^{\circ}\text{C}$ (between -40 and $+70^{\circ}\text{C}$);
Anemometer of Delta Ohms	± 0.05 m/s ($k=2$) for an air velocity of 1 m/s;
Ultrasonic anemometer Windsonic WS3 of Gill Instruments	$\pm 2\%$ for wind velocity range between 0 and 60 m/s; $\pm 3\%$ for wind direction range between 0 and 359° ;
Pyranometer CMP11 of Kipp & Zonen	$\pm 1.4\%$;

Hukseflux HFP01-L heat flux sensor of Campbell scientific

Within -15% to +5% in most common soils for 12h;

BCAM thermal camera of Flir Systems

$\pm 2^{\circ}\text{C}$ or $\pm 2\%$ of reading (between -10 and $+100^{\circ}\text{C}$) (default auto-adjusted emissivity: 0.96);

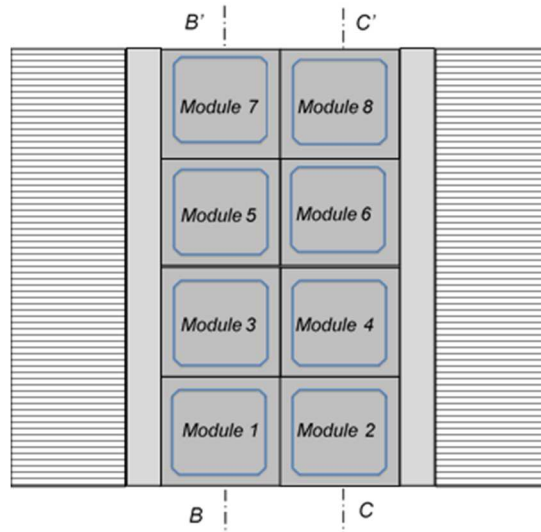
34972A datalogger of Agilent

$\pm 0.0035\%$ of reading $\pm 0.005\%$ of selected range;

SHARKY 775 energy meter of DHIEL

$\pm 10\%$ on thermal power (positive values for heating periods and negative values for cooling periods).

325

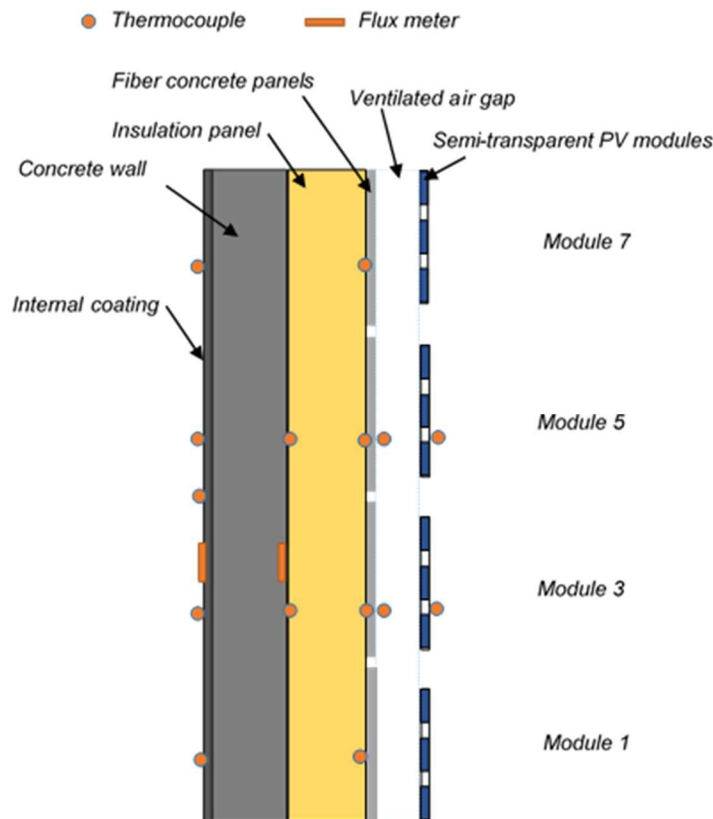


(a)

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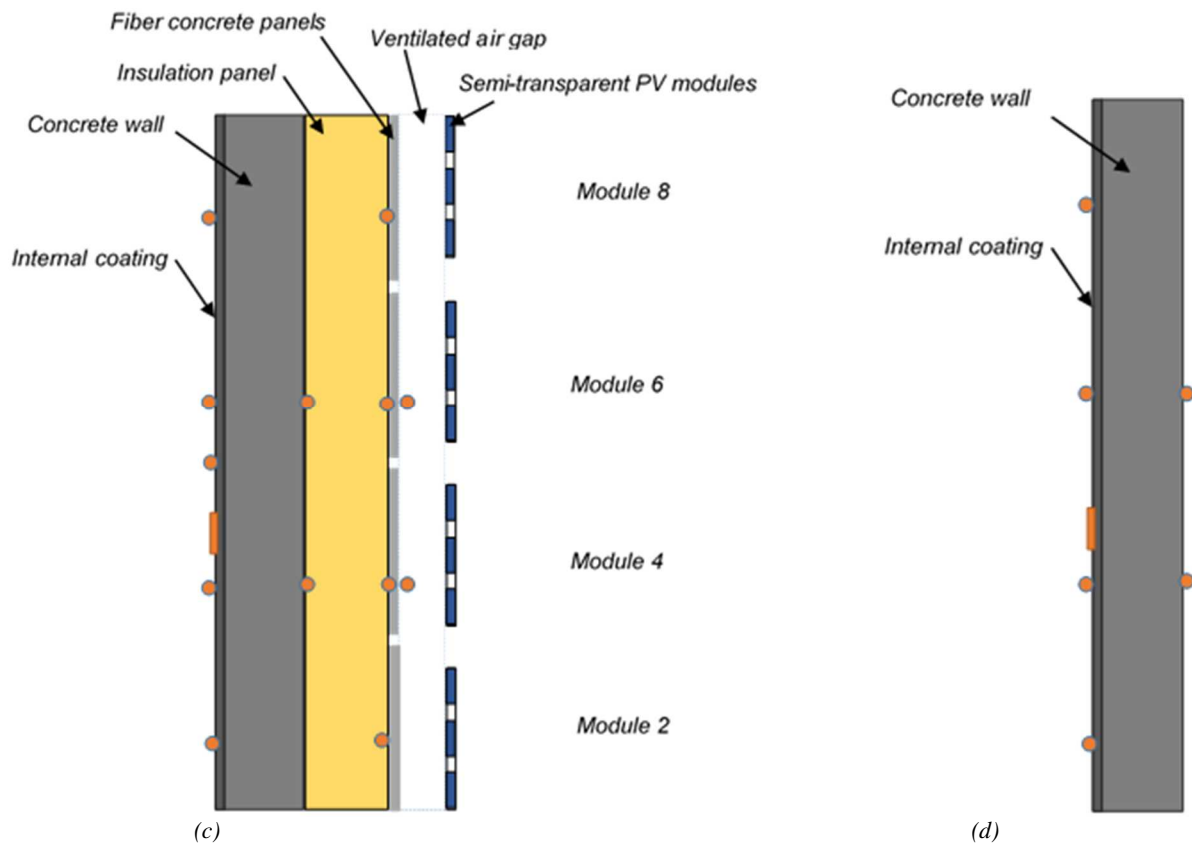
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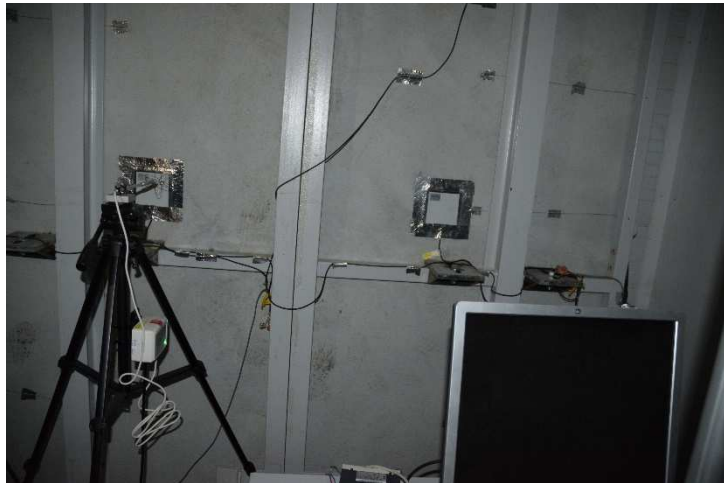
(b)

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Figure 6: Schemes of the photovoltaic facade front view on test cell 4 (a) and its vertical sections (b: section B'-B and c: section C'-C) and of the vertical section of the reference facade on test cell 3 (d) (with orange lines for flux meters and orange dots for thermocouples)



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Figure 7: Photograph of the interior of the test cell 4 with some thermocouples and flux meters (behind PV module 3 (at the right side) and at the level of the interface between PV modules 3 and 4 (at the left side)) on the internal coating and with the anemometer of Delta Ohms.

3.2. Parameters considered for the analysis of the BIPV system electrical performance

347

348 Three main parameters were used for the analysis of the measured electrical data, namely, the
349 performance ratio after the micro-inverter Pr_{ac} (-), the electrical efficiency η_{pv} (-) and the final yield Y_f
350 (kWh/kWp), which are provided respectively by equation 1, equation 2 and equation 3. The
351 performance ratio permits to evaluate the energy production of the system compared to STC
352 conditions (corresponding to a Pr_{ac} value of 1). More precisely, the performance ratio permits to take
353 into account the impact of various operating conditions parameters (such as inverter issues, shading,
354 wiring losses, cell mismatch, modules temperature or outages) on the PV system electrical energy
355 production (Khalid et al., 2016; Assoa et al., 2017; Cubukcu and Gumus, 2020).

356 The electrical efficiency is the ratio between the electrical energy produced and the solar energy
357 received by the PV system area.

358 The final yield Y_f is the ratio between the electrical energy produced and the nominal power
359 installed and permits to evaluate the number of times the PV system has produced an electrical
360 energy equal to its nominal power on a defined period.

361

$$Pr_{ac} = (E_{ac}/P_{max})/(E_i/G_{STC}) \quad (1)$$

362

363

$$\eta_{PV} = E_{ac}/(E_i \cdot S_{PV}) \quad (2)$$

364

365

$$Y_f = E_{ac}/P_{max} \quad (3)$$

366

367

368 With E_{ac} , the electrical energy produced in AC (kWh) that is the numerical integration of the measured
369 electrical power produced by the PV field on a defined period (time step in hour), E_i the cumulated
370 incident solar energy (kWh/m²) obtained with the numerical integration of the measured incident total
371 solar radiation received at the front side of the PV modules on the same period (time step in hour),
372 G_{STC} the incident solar radiation in standard tests conditions (STC) (equal to 1 kW/m²), P_{max} the
373 nominal power (kWp) of the PV modules front side obtained with flash-tests (see table 2) and S_{pv} the
374 PV field area including, here, only the PV modules front glass areas (m²).

375 Moreover, in order to evaluate the impact of bifaciality on the BIPV field electrical performance,
376 equation 4 was used to calculate an electrical power (noted P_{pvmf}) produced by a PV field comprising
377 monofacial PV modules with electrical characteristics similar to the ones of the studied bifacial PV
378 modules front side (see equation 4) (Kaldellis et al., 2014). A theoretical electrical efficiency η_{PV1} was
379 estimated, in this case, based on T_{pvmean} , the bifacial PV field measured mean temperature
380 (corresponding to an average of the PV module 3 and the PV module 5 measured temperatures) and
381 neglecting the difference of temperatures between the bifacial and the monofacial PV modules (Chow,
382 2003) (see equation 5):

383

$$P_{pvmf} = \eta_{pv1} \cdot G_i \cdot S_{pv} \cdot Cp \quad (4)$$

384

$$\eta_{pv1} = \eta_{ref} \cdot (1 - \beta_r \cdot (T_{pvmean} - T_{pvref})) \quad (5)$$

386

387 With η_{ref} and SPV respectively, the reference PV modules efficiency (of 8.7% in STC, here) and the PV
 388 modules area (m^2). G_i is the incident total solar radiation (W/m^2) and β_r is the temperature coefficient
 389 (supposed equal to $-0.37\%/^{\circ}C$, for a monocrystalline silicone PV module). T_{pvref} is the reference PV
 390 module temperature (of $25^{\circ}C$, in STC).

391 Then, a performance loss coefficient C_p was considered and supposed to be equal to 0.62 (mean
 392 value used at standard test conditions (STC)) in order to take into account losses due to grid-
 393 integration (conversion from DC to AC power, DC and AC electrical systems, inverter losses...).
 394 (Marion et al, 2005)

395

396 Finally, a bifacial gain BG was evaluated using equation 6:

397

$$BG = (E_{ac} - E_{pvmf}) / E_{pvmf} \quad (6)$$

399

400 With E_{pvmf} the electrical energy production (kWh) of the monofacial BIPV facade calculated based on
 401 the numerical integration of equation 5 on a defined period (time step in hour).

402

403

404 **4. Analysis of the bifacial photovoltaic PV module thermal behavior**

405

406 In this section, the thermal behavior of the bifacial photovoltaic facade is analyzed on daily and
 407 monthly bases focusing on the PV modules. The PV module 3 and the PV module 5 were mainly
 408 studied since they were the most instrumented (see figure 6 b). The PV module 3 is located below the
 409 PV module 5 on the solar facade (see figure 6 a).

410

411 *4.1. Analysis of the bifacial PV modules thermal behavior on a daily base*

412

413 In July 2019, the solar radiation in the vertical plane was up to $554.2 W/m^2$ with a cumulated total
 414 solar energy of $51 kWh/m^2$. It is to be noted that due to FACT tool annual maintenance, some
 415 measured data were missing from the 8th to the 21st of July (see figure 8 a). The ambient temperature
 416 was comprised between $14.7^{\circ}C$ and $40.7^{\circ}C$ (see and figure 8 b).

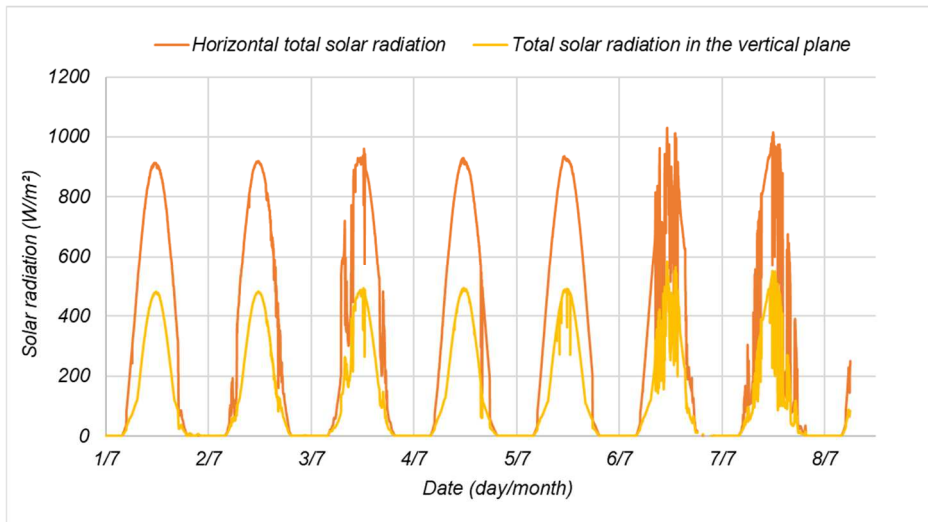
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418 In January 2019, the maximum solar radiation in the vertical plane was of $295 W/m^2$ with a
 419 cumulated total solar energy of $56 kWh/m^2$ (see figure 9 a) and the ambient temperature was between
 419 $-5^{\circ}C$ and $12.1^{\circ}C$ (see figure 9 b).

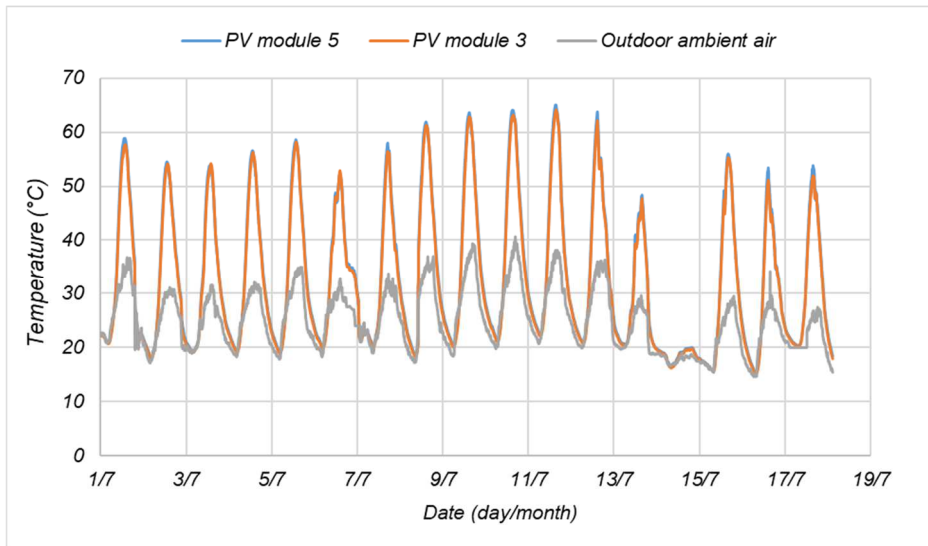
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421 Figure 8 b and figure 9 b present daily temperatures profiles of the PV module 3 and the PV
 422 module 5 during respectively, a month in warm period (in July 2019) and a month in cold period (in
 422 January 2019) and the corresponding outdoor ambient air temperature profiles.

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(a)



(b)

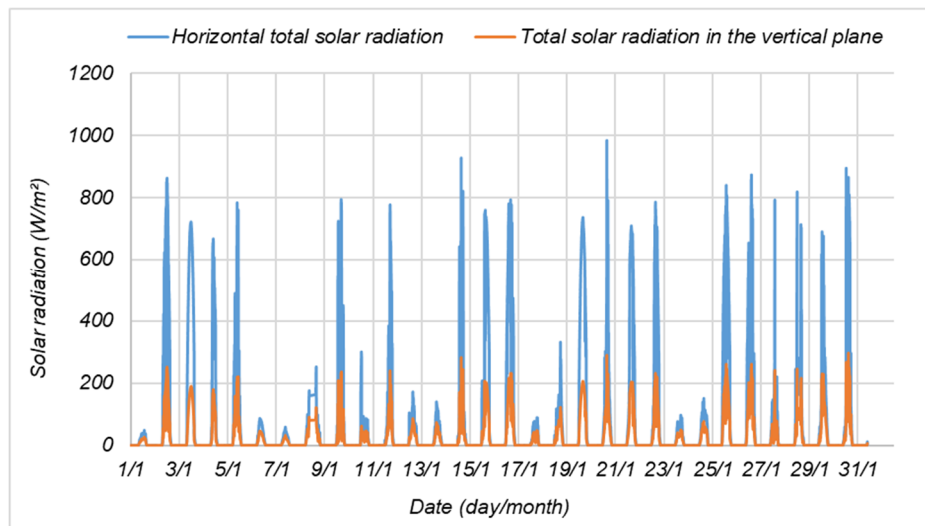
Figure 8: Horizontal total solar radiation, total solar radiation in the vertical plane (a), temperatures profiles of PV modules 3 and 5 and outdoor ambient air temperature (b) during a month in warm period (in July 2019).

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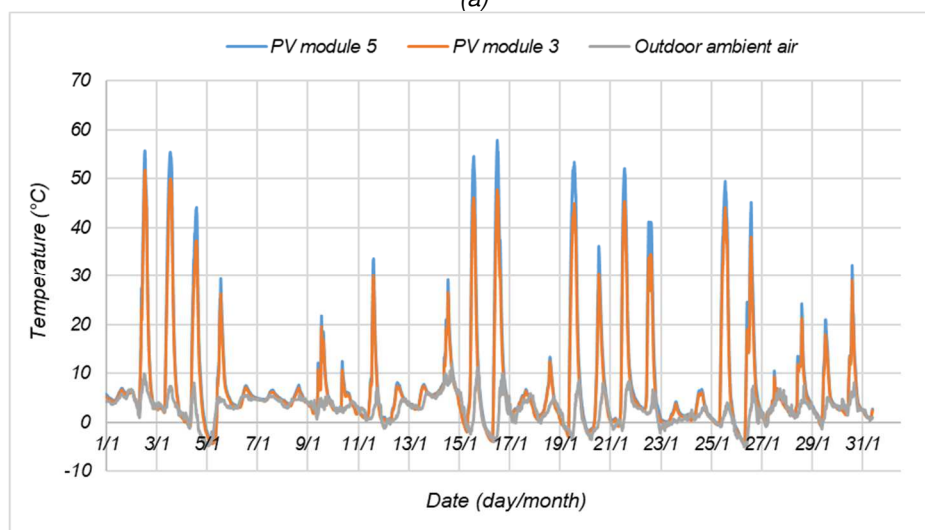
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(a)



(b)

Figure 9: Horizontal total solar radiation, total solar radiation in the vertical plane (a), temperatures profiles of PV modules 3 and 5 and outdoor ambient air temperature (b) during a month in cold period (in January 2019).

Figure 8 b and figure 9 b show that the PV module 3 temperature was comprised between -4.5°C and 51.8°C in January and between 15.2°C and 64.2°C in July, while the PV module 5 temperature was comprised between -4.3°C and 57.9°C in January and between 15.5°C and 65.1°C in July. The PV module 5 temperature was higher than the PV module 3 temperature, which could be explained by the predominant rising stack effect (natural ventilation due to air pressure drops and wind effects at the inlets and the outlets of the air gap) (Brinkworth et al., 2000) in the discontinuous air gap (Sanjuan et al., 2011b) compared to site albedo impact (solar radiation reflected by site elements (ground, front building, mountains and airport)). In January, the thermal gradient between the PV module 3 and the PV module 5 was comprised between -0.2°C and 10.4°C with higher differences during daylight hours. However, in July, this thermal gradient was reduced (between -1.3°C and 3.7°C) due to the most important effect of site albedo increasing PV modules temperature at the bottom of the facade.

Then, the PV module 3 heating compared to outdoor ambient temperature was between -3.7°C and 28.7°C in July and between -5.3°C and 50.3°C in January, with negative values during night, as

459 expected, due to heat transfer by radiation with the sky. The PV module 5 heating was between -3.4°C
460 and 29.4°C in July and between -5.2°C and 60.4°C in January. (See figure 8 b and figure 9 b)

461 Furthermore, the PV modules thermal behavior was analyzed on a monthly base.

462

463 4.2. Analysis of the bifacial PV modules thermal behavior on a monthly base

464

465 Table 4 presents the monthly maximum temperatures of the PV module 3 and the PV module 5 on
466 the testing period.

467

468 *Table 4: Monthly maximum temperatures of the PV module 3 (Tpv3) and the PV module 5 (Tpv5) and absolute*
469 *difference of temperatures (dTpv) taking Tpv5 as reference from December 2018 to December 2019.*

Month and year	Tpv3 (°C)	Tpv5 (°C)	dTpv (°C)
December 2018	51.7	58.2	6.5
January 2019	51.8	57.9	6.1
February 2019	60.6	66.8	6.2
March 2019	61.6	66.9	5.2
April 2019	58.1	62.0	3.9
May 2019	52.3	53.4	1.2
June 2019	61.2	62.2	1.1
July 2019	64.2	65.1	0.9
August 2019	66.2	68.6	2.4
September 2019	66.4	70.2	3.8
October 2019	64.4	69.3	4.9
November 2019	50.9	57.9	7.0
December 2019	51.0	57.7	6.7

470

471 According to results of table 4, the PV module 5 reached maximum temperatures of nearly 69.3°C
472 in autumn (in October 2019), 66.9°C in winter (in March 2019), 62.2°C in spring (in June 2019) and
473 70.2°C in summer (in September 2019) and thus was warmer than the PV module 3 (with respectively,
474 64.4°C, 61.6°C, 61.2°C and 66.4°C).

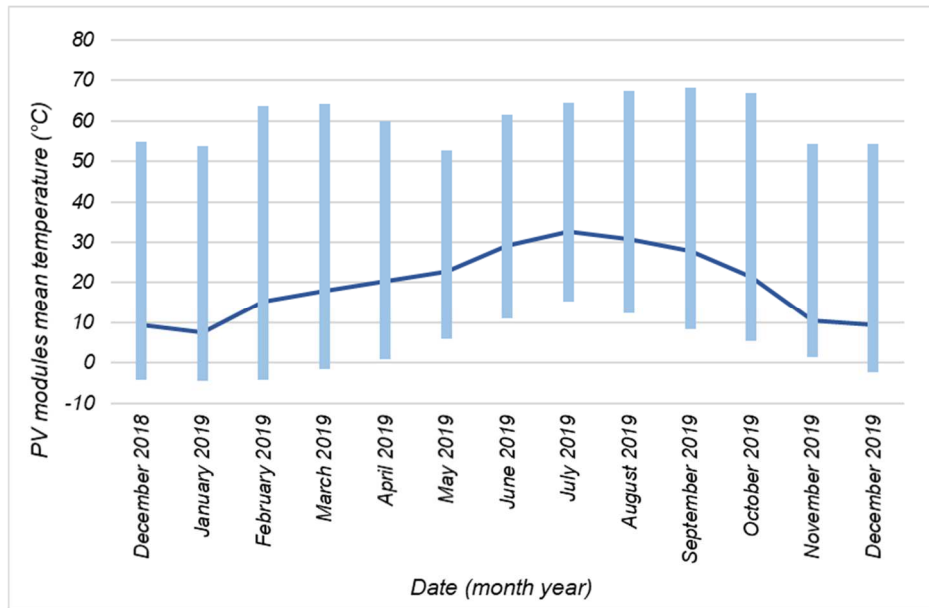
475 The gradient of temperatures between the two PV modules was comprised between nearly 0.9°C
476 and 7°C on the testing period, which could also be explained by the stack effect in the discontinuous
477 air gap and by the solar radiation reflected by the ground on the solar facade (albedo) (see table 4).
478 The lower thermal gradients observed in warm period (between 0.9°C and 3.9°C from April 2019 to
479 August 2019) could be due to an albedo effect enhanced by the higher sun height and solar radiation
480 intensities (see table 4 and figure 8 b).

481 In mid-season and cold period, the higher gradients of temperatures between the PV module 5 and
482 the PV module 3 (between 3.8°C and 7°C from December 2018 to March 2019 and from September
483 2019 to December 2019) could be due to lower sun height limiting the albedo effect (see table 4).

484

485 Then, figure 10 presents the monthly variations and the average values of the PV field mean
486 temperatures (obtained based on the PV module 3 and the PV module 5 measured temperatures)
487 from December 2018 to December 2019 (See figure 10). Temperature sensors were stuck on the front

488 glass edge, so, the temperatures of PV cells could be slightly higher than the measured values since
489 the thermal conductivity of glass (of nearly 1 W/m.K) is lower than the one of the monocrystalline
490 silicon PV cells (between 100 W/m.K and 140 W/m.K).
491



492
493 *Figure 10: Monthly variations of the PV field mean temperature based on the PV modules 3 and 5 front glass*
494 *temperatures and monthly average values (dark blue line) from December 2018 to December 2019.*

495
496 As expected, in cold season, lower PV field monthly average temperatures are observed (from
497 December 2018 to March 2019 and from October 2019 to December 2019) with values comprised
498 between 7.4°C in January 2019 and 21.3°C in October 2019. In warm season (from April 2019 to
499 September 2019), the PV field monthly average temperatures were comprised between 20.4°C in April
500 2019 and 32.6°C in July 2019.

501 Considering the whole testing period, the PV field mean temperatures varied between -4.4°C in
502 January 2019 and 68.3°C in September 2019. In warm season, the PV field mean temperatures were
503 comprised between 0.9°C in April 2019 and 68.3°C in September 2019. The higher level of
504 temperatures compared to cold season is due to more important solar radiation intensities and outdoor
505 ambient air temperatures. In cold season, the PV modules mean temperatures were between -4.4°C
506 in January 2019 and 66.9°C in October 2019. High temperatures values noted in cold season could be
507 explained by the better sun exposure (lower sun height) for a facade integrated system and by the
508 lower stack effect in the air gap (lower thermal gradient between the top and the bottom of the facade).
509 (See figure 10)

510
511 Then, since all photovoltaic modules could not be instrumented, a thermal camera was used to
512 analyze the gradient of temperatures along the bifacial facade in a warm day and in a cold day.

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516 **5. Analysis of the temperature distribution on the bifacial photovoltaic facade**

517

518 The thermal behavior of the bifacial photovoltaic facade is analyzed on a daily base focusing on the
519 whole system. The temperature distribution on the indoor side and the outdoor side of the PV facade
520 was studied using a thermal camera (see table 3) in order to estimate the impact of stack effect and of
521 site albedo and to observe the possible existing thermal bridges between the bifacial PV facade basic
522 elements. A day with a low level of solar radiation and a day with a high level of solar radiation were
523 considered.

524

525 *5.1. Temperature distribution at low solar radiation level*

526

527 Figure 11 presents the thermal images obtained on a day in April with low level of solar radiation
528 from 1:58 pm to 2:01 pm. The mean solar radiation on the vertical plane was of nearly 58.3 W/m² (of
529 nearly 111.1 W/m² on the horizontal plane), the mean outdoor ambient air temperature was of 15.1°C
530 and the mean wind velocity was of nearly 2 m/s on this short period.

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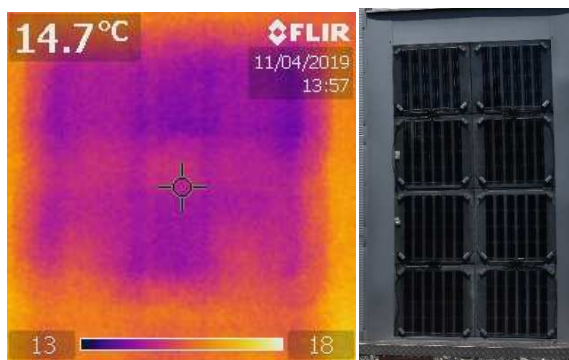
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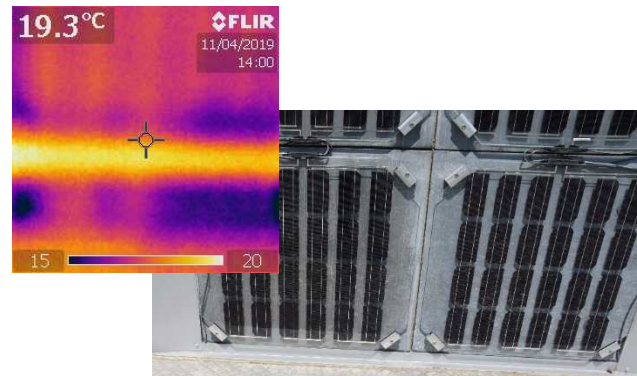
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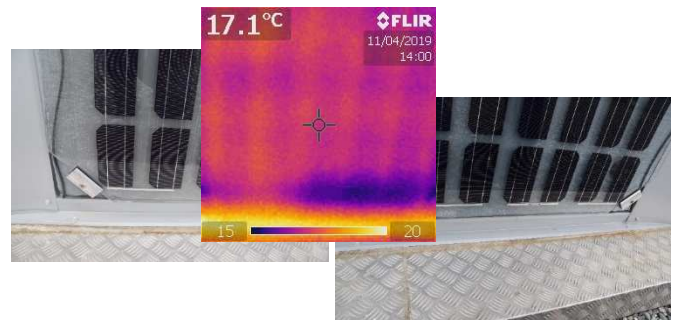
(a)



(b)



(c)



(d)

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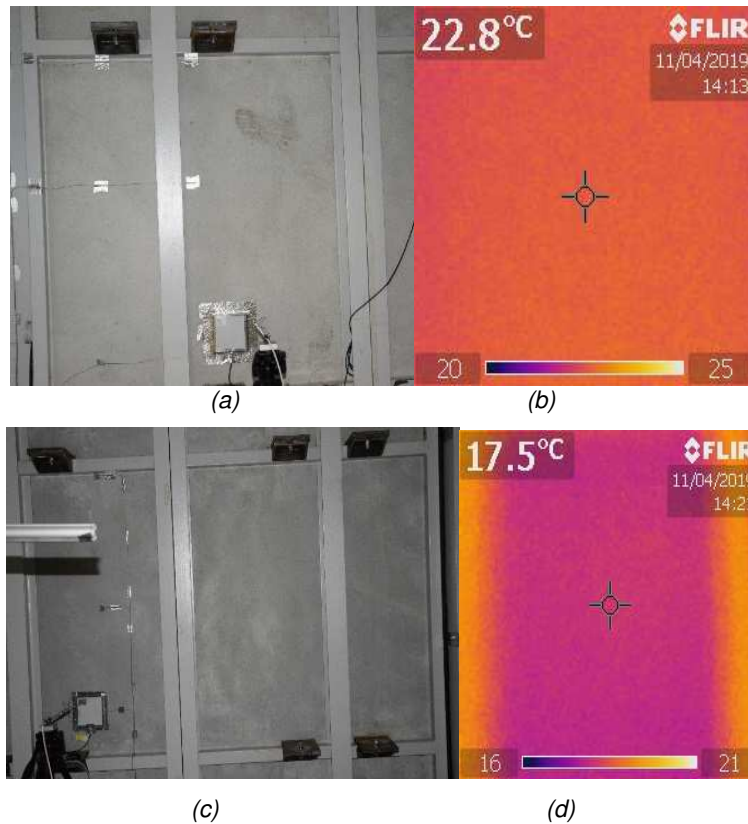
565

Figure 11: Thermal images and photographs of the BIPV facade on test cell 4 from 1:58 pm to 2:00 pm on a day in April with low solar radiation: (a) on the PV field; (b) at the interface between PV modules 1, 2, 3 and 4; (c) on fasteners of PV module 3 and (d) on PV module 1 and PV module 2.

At low solar radiation, a reduced gradient of temperatures is noted along the facade (limited temperature range of nearly 5°C) (see figure 11 a) with the fasteners at nearly 12.7°C (see figure 11 c), the PV module 1 and the PV module 2 at 17.1°C (see figure 11 d) and the concrete wall between the PV modules 1, 2, 3 and 4 at nearly 19.3°C (see figure 11 b).

566 The slightly higher temperature observed at the interfaces between the bifacial photovoltaic facade
567 basic elements could be explained by the direct heat storage in the concrete wall, although the sun
568 exposed areas are very thin (see figure 11 b).
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574 *Figure 12: Photographs and thermal images of the internal coatings of the south-oriented facades of test cell 4 (a*
575 *and b) and test cell 3 (c and d) from 2:12 pm to 2:21 pm on a day in April with low solar radiation.*

576
577

578 Figure 12 shows the photographs (see figure 12 a and figure 12 c) and the thermal images (see
579 figure 12 b and figure 12 d) of the internal coatings of the solar facade on test cell 4 and the reference
580 facade on test cell 3 from 2:12 pm to 2:21 pm on the same day. The mean solar radiation on the
581 vertical plane was of 47 W/m² nearly (124 W/m² nearly on the horizontal plane), the mean ambient
582 temperature was of 14.8°C nearly and the mean wind velocity was of nearly 2.3 m/s on this period.

583 The temperature at the center of the internal coating was of 17.5°C in test cell 3 (reference) (see
584 figure 12 d) and of 22.8°C in test cell 4 (see figure 12 b), in these conditions. Thus, the integration of
585 the bifacial photovoltaic facade has led to an increase of the coating temperature of nearly 5.3°C
586 during the testing period and to a reduction of heat transfers through the wall since its temperature is
587 closer to the setpoint temperature in April 2019.

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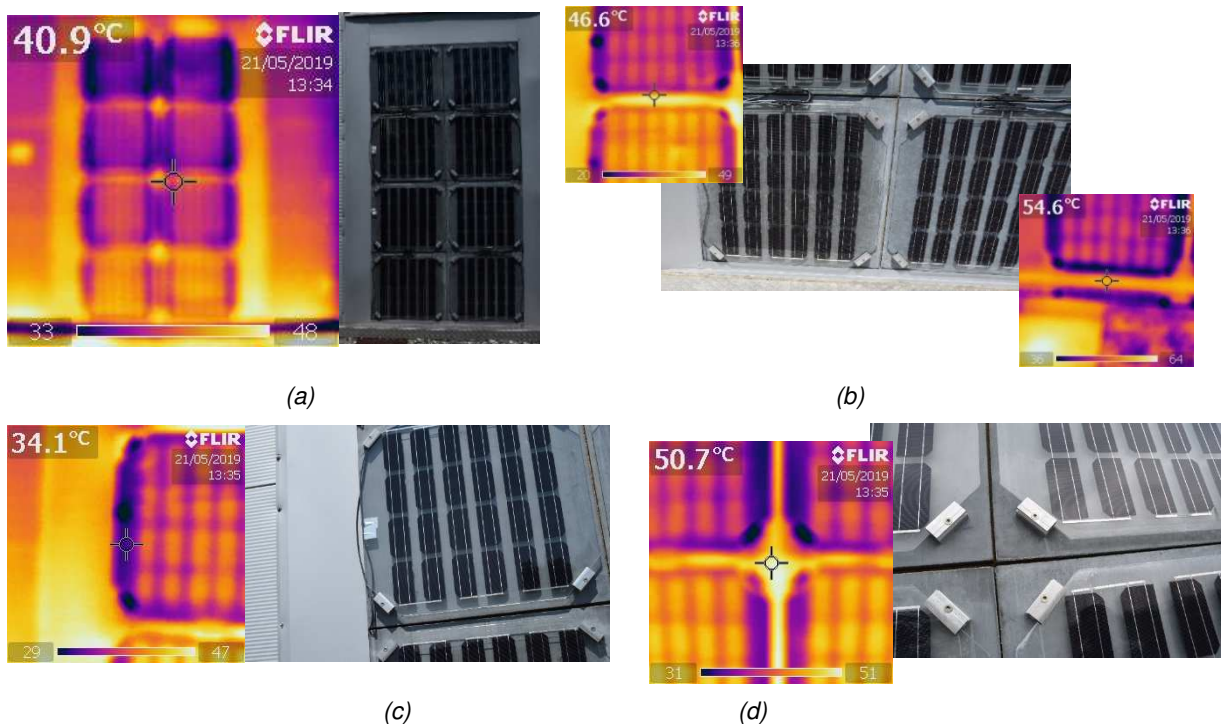
5.2. Temperature distribution at high solar radiation level

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592 A similar analysis was performed on a day in May 2019 with more important solar radiation from
593 1:34 pm to 1:44 pm. The mean solar radiation on the vertical plane was of 365 W/m² nearly (of nearly
594 661 W/m² on the horizontal plane), the mean ambient temperature was of nearly 21.1°C and the mean
595 wind velocity was of nearly 2.8 m/s.

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Figure 13 presents the thermal images and the photographs of the BIPV facade on test cell 4, during this short period (see figure 13).



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Figure 13: Thermal images and photographs of the BIPV facade on test cell 4 from 1:34 pm to 1:44 pm on a day in May with high solar radiation: (a) on the PV field; (b) at the interface between PV modules 1, 2, 3 and 4; (c) on fasteners of PV module 3 and (d) at the interface between PV modules 3, 4, 5 and 6.

606 A more important thermal gradient is observed, as expected, along the BIPV facade with
607 temperatures of fasteners of nearly 34.1°C (see figure 13 c), of an edge of PV module 4 of nearly
608 40.9°C (see figure 6 a and figure 13 a), of the concrete wall at the interface of PV modules 1, 2, 3 and
609 4 comprised between 46.6°C and 54.6°C (see figure 13 b) and of the concrete wall at the interface of
610 PV modules 3, 4, 5 and 6 of nearly 50.7°C (see figure 13 d).

611 Except for the PV modules located at the bottom of the wall, the PV facade temperature increases
612 slowly from bottom to top due to both the stack effect and the site albedo effect, which are more
613 significant at high solar radiation than at low solar radiation, as expected. Since the air gap is
614 discontinuous and comprises different entries, the gradient of temperatures is not uniform from bottom
615 to top like in a conventional PV ventilated facade. Indeed, the outdoor air entering the air gap is cooler
616 than the PV modules and the fiber concrete panel and thus, reduces their temperatures (Sanjuan et al.,
617 2011b). According to Sanjuan et al. (2011a), in the case of the studied open joint ventilated solar
618 facade, this outdoor air tends to enter in the air gap at the bottom and the top of the first row of PV
619 modules (see PV modules 1 and 2 in figure 6 a) and to exit at the bottom and top of the upper row of
620 PV modules (see PV modules 7 and 8 in figure 6 a). (See figure 2 c)

621 Moreover, figure 13 a highlights that the existing site albedo seems to have, here, a preponderant
622 influence compared to the stack effect at high solar radiation conditions and in warm period due to

623 higher sun height. The albedo effect is, as expected, more important close to the ground (which is
624 composed of white and light grey gravels with a high reflection coefficient) and decreases gradually
625 from the bottom to the top of the façade (Raybaud et al., 2019).

626 Since the PV modules are connected in series on the micro-inverter, this important thermal
627 gradient along the façade could reduce the system electrical performance compared to a more uniform
628 facade temperature distribution.

629 A darker ground could limit this effect and in the case of bifacial modules installation, a thicker air
630 gap could increase the incident solar radiation rate reflected by the fiber concrete panel and reaching
631 the PV modules backside. Therefore, a suitable choice of the surrounding ground type close to the PV
632 facade could improve its thermal behavior and then its electrical production. Moreover, the increase of
633 the air gap thickness (from 2 cm to 5 cm, for example) could improve the cooling of PV modules at
634 their rear side (Lau et al., 2018) and thus their electrical production.

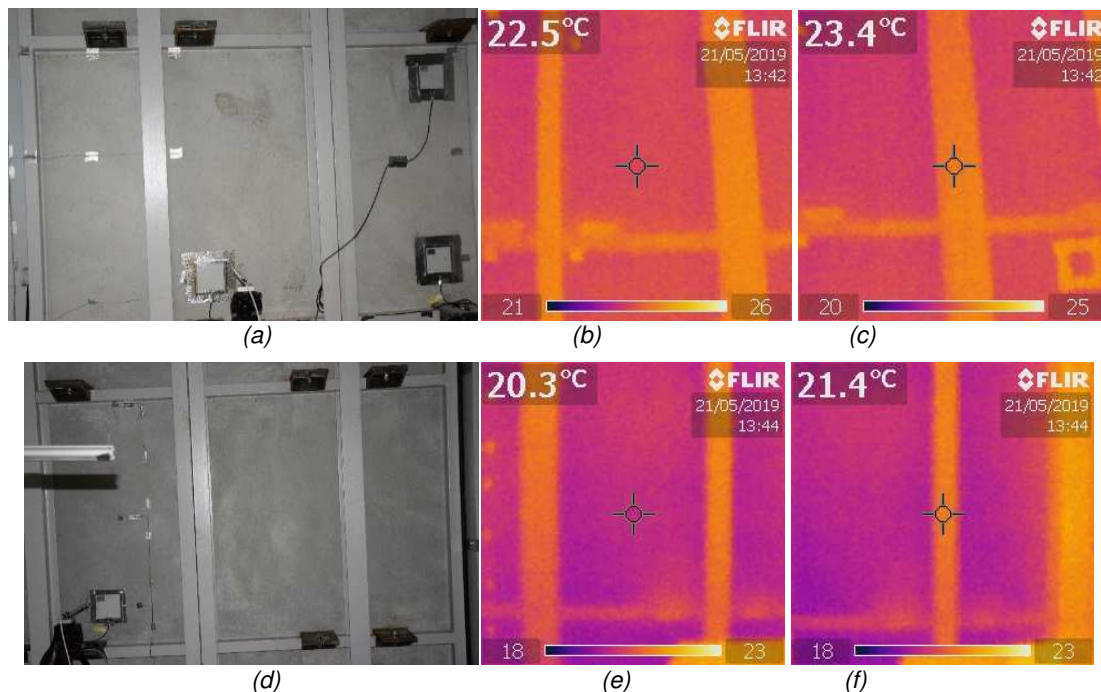
635 These approaches could be included at design phase for the architectural development of fully
636 integrated BIPV solutions (Farkas et al., 2013)

637

638 Finally, figure 14 shows the thermal images and the photographs of the internal coatings of the
639 solar facade on test cell 4 and of the reference facade on test cell 3 at higher solar radiation between
640 1:42 pm and 1:44 pm on the same day (see figure 14). The mean solar radiation on the vertical plane
641 was of 500 W/m^2 nearly (of 943 W/m^2 nearly on the horizontal plane), the mean outdoor ambient air
642 temperature was of 22.2°C and the mean wind velocity of nearly 1.24 m/s , on this period.

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648 *Figure 14: Photographs and thermal images of the internal coatings of the south-oriented facades of test cell 4 (a,*
649 *b and c) and of test cell 3 (d, e and f) obtained with a thermal camera from 1:34 to 1:44 pm on a day in May with*
650 *high solar radiation.*

651

652 As expected, lower surface temperatures are noted in test cell 3 (of 20.3°C for the metal structure
653 and of 21.4°C for the internal coating) (see figure 14 e and figure 14 f) compared to test cell 4 (of
654 23.4°C for the metal structure and of 22.5°C for the indoor coating) (see figure 14 b and figure 14 c).
655 Results show that at higher solar radiation, there is a lower increase of coating temperature (of 2.2°C
656 nearly) after integration of the bifacial PV facade elements, on the selected testing period. This seems
657 to be due to the more optimal weather conditions (solar radiation and outdoor ambient air temperature)
658 permitting an improved heat storage in the reference concrete wall on test cell 3 and to a better heat
659 extraction (stack effect) in the solar facade air gap on test cell 4 leading to a better cooling of the fiber
660 concrete wall and of the bifacial PV modules.

661
662 At low and high solar radiation levels, the uniformity of the internal coating temperature distribution
663 (see figure 12 and figure 14) compared to the important thermal gradient on the outside (see figure 10
664 and figure 12) of the bifacial BIPV facade highlights also that the developed system configuration
665 permits satisfactorily to limit the impact of the possible thermal bridges at the interfaces of the PV
666 basic elements. It is to be noted that results obtained with thermal camera are consistent with the
667 values of figure 8 b, figure 9 b and table 4.

668
669

670 6. Analysis of the bifacial photovoltaic modules electrical performance

671 6.1. Analysis of the bifacial photovoltaic facade electrical performance

672
673 The electrical production of the PV field of 456 Wp was measured mainly in order to estimate the
674 impact of building integration on bifacial PV modules performance. Table 5 summarizes the system
675 monthly electrical performance after micro-inverter (AC) (energy production, final yield, performance
676 ratio and efficiency), the outdoor ambient air temperature and the cumulated incident solar energy
677 from December 2018 to December 2019 and their annual cumulated or mean values.

678
679
680 *Table 5: Monthly, period and annual (cumulated or mean) electrical performance after micro-inverter (AC) of the*
681 *bifacial BIPV facade (electrical energy production, final yield, performance ratio and electrical efficiency), outdoor*
682 *ambient air temperature (minimum, maximum and mean values) and incident total solar energy from December*
683 *2018 to December 2019.*

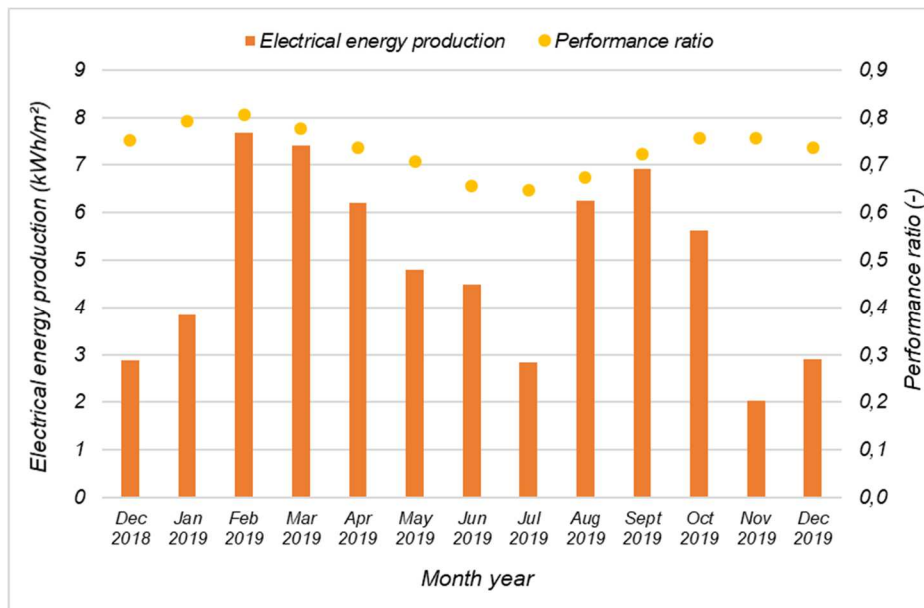
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Month	Ambient air temperature ([min; max]; mean) (°C)	Cumulated total solar energy in the vertical plane (kWh/m ²)	Cumulated electrical energy production (AC) (kWh/m ²)	Final yield (kWh/kWp)	Performance ratio (-)	Electrical efficiency (%)
December 2018	[-4.2;16.4]; 5.7	44	2.9	33.4	0.8	6.5
January 2019	[-5; 12.1]; 2.8	56	3.8	44.4	0.792	6.8
February 2019	[-4.5; 21.2]; 4.8	110	7.7	88.9	0.806	7.0
March 2019	[-1.7; 24]; 9.1	111	7.4	85.8	0.776	6.7
April 2019	[0.4; 27]; 12	98	6.2	71.9	0.737	6.4

May 2019	[0.6; 28.1]; 14.2	79	4.8	55.6	0.707	6.1
June 2019	[9.2; 38.2]; 21.6	80	4.5	52.1	0.655	5.6
July 2019	[14.7; 40.7]; 11.6	51	2.8	32.8	0.647	5.6
August 2019	[11.2; 37.1]; 22.1	108	6.2	72.4	0.673	5.8
September 2019	[7.5; 32.1]; 18.3	111	6.9	80.1	0.723	6.2
October 2019	[5; 26.1]; 14.2	86	5.6	65.2	0.756	6.5
November 2019	[0; 59]; 29.5	31	2.0	23.5	0.756	6.5
December 2019	[2.0;17.5]; 6.1	46	2.9	33.8	0.736	6.3
Total or mean values (from December 2018 to December 2019)	-	1009 (total)	63.8 (total)	739.9 (total)	0.730 (mean)	6.3 (mean)
Annual total or mean values (from December 2018 to November 2019)	-	964 (total)	60.9 (total)	706.1 (total)	0.732 (mean)	6.3 (mean)

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Figure 15 presents the monthly electrical energy production and the performance ratio after micro-inverter (AC) of the system studied on the selected period.



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Figure 15: Monthly electrical energy production and performance ratio after micro-inverter (AC) of the bifacial BIPV facade from December 2018 to December 2019.

Table 5 and figure 15 indicate, as expected, a decrease of performance in warm season (from April to September 2019) due to higher levels of the PV modules temperature and more optimal incident angles of solar radiation.

The monthly solar energy produced was comprised between 31 kWh/m² and 111 kWh/m² nearly during the two cold seasons and between 51 kWh/m² and 111 kWh/m² nearly in warm season. The cumulated solar energy on the selected period was of 1009 kWh/m² nearly. The lower results obtained in July 2019 and November 2019 are due to monitoring issues and to the site maintenance period.

699

700 In cold season, from December 2018 to March 2019 and from October 2019 to December 2019,
701 the monthly electrical energy production was comprised between 2 kWh/m² and 7.4 kWh/m² nearly
702 corresponding to electrical efficiencies between 6.3% and 7% and to performance ratio between 0.736
703 and 0.806. The monthly final yield was between 23.5 kWh/kWp and 88.9 kWh/kWp and maximum
704 values were obtained in February 2019.

705 In warm season, from April 2019 to September 2019, the monthly electrical energy production was
706 comprised between 2.8 kWh/m² and 6.9 kWh/m² corresponding to electrical efficiencies between 5.6%
707 and 6.4% and to performance ratio between 0.647 and 0.737. The monthly final yield was between
708 32.8 kWh/kWp and 80.1 kWh/kWp with maximum values in September 2019 (See table 5 and figure
709 15). The variations of performance ratio values on the testing period highlight optimal electrical
710 performance in cold season, as expected.

711 The cumulated electrical energy produced was of 63.8 kWh/m² considering the whole period and of
712 60.9 kWh/m² on the year (from December 2018 to November 2019) with 31.5 kWh/m² in warm season
713 (from April to September 2019) and 29.4 kWh/m² in cold periods (from December 2018 to March 2019
714 and from October to November 2019). So, although the less optimal operating conditions in warm
715 season for a façade integrated system, the bifacial photovoltaic field permits globally close cumulated
716 electrical energy productions in cold and warm seasons. This could be explained by the rear side
717 additional production of bifacial PV modules, which seems to increase in warm season thanks to the
718 higher impact of site albedo (see figure 13 a). The lower cumulated energy production in cold season
719 seems to be due to monitoring issue.

720 The PV system mean annual efficiency was of 6.3% and the total annual final yield was of 706.1
721 kWh/kWp (of 739.9 kWh/kWp on the whole period). The mean annual value of performance ratio of
722 0.73 indicates that the level of ventilation of PV modules at the rear side is average due to the low air
723 gap thickness (of 2 cm). Nevertheless, this value indicates also that the facade integrated bifacial PV
724 field provided nearly 73% of its expected electrical energy production in STC conditions and in a non-
725 integrated configuration, and up to 80.6% in February, which is satisfactory.

726

727 *6.2. Impact of bifaciality on the photovoltaic system electrical performance*

728

729 Then, the monthly impact of bifaciality on the photovoltaic system electrical performance was
730 analyzed on the testing period based on a comparison with a photovoltaic facade comprising
731 monofacial PV modules with electrical characteristics in STC similar to the ones of the bifacial PV
732 modules front side. Equation 4 and equation 5 were used to calculate the electrical energy production
733 of the monofacial facade since this installation could not be tested on site and the monthly, annual,
734 and period bifacial gains were obtained with equation 6. (See equation 4, equation 5, equation 6 and
735 table 6)

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741 *Table 6: Monthly, period and annual cumulated electrical performance after micro-inverter (AC) (kWh) of the*
742 *bifacial BIPV façade and of the monofacial BIPV façade and bifacial gains from December 2018 to December*
743 *2019*

Month	Cumulated electrical energy production of the bifacial BIPV facade (kWh)	Cumulated electrical energy production of the monofacial BIPV facade (kWh) (calculated)	Bifacial gain (%)
December 2018	15.9	12.5	26.38
January 2019	20.3	15.8	28.09
February 2019	40.6	29.5	37.49
March 2019	39.1	29.9	30.77
April 2019	32.8	26.6	23.19
May 2019	25.4	22.2	14.08
June 2019	19.8	19.0	4.51
July 2019	6.8	6.1	11.03
August 2019	33.0	28.2	17.28
September 2019	33.0	29.1	13.48
October 2019	29.7	23.0	29.00
November 2019	10.7	8.7	23.35
December 2019	15.4	12.8	20.46
Period (cumulated)	322.3	263.4	22.38
Year (cumulated)	307.0	250.62	22.48

744

745 Table 6 shows that the monofacial PV system has a lower electrical energy production than the
746 bifacial PV system, as expected.

747 The bifacial gains were comprised between 4.51% (in June 2019) and 37.49% (in February 2019).

748 The mean bifacial gains on the selected period and on the year were of respectively, nearly
749 22.38% and 22.48%, which are coherent with the one obtained numerically by Soria et al. (2015) for a
750 facade integration (of nearly 25%). These satisfactory results validate the relevance of the choice of
751 the smooth fiber concrete layer as reflective surface. Nevertheless, a comparison with data measured
752 on a monofacial PV facade should be performed in order to confirm the observations since the
753 calculated results depend on the performance loss coefficient C_p considered.

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755 Then, the impact of the studied system on the building energy consumption for heating and cooling
756 was estimated experimentally.

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765 7. Impact on the building energy performance

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767 7.1. Analysis of the building energy consumption

768 The impact of the solar prototype on the test cell energy consumption was also evaluated from
769 December 2018 to December 2019. Table 7 summarizes the measured monthly and period cumulated
770 results of energy consumption for heating and cooling and of the total energy consumption needed to
771 maintain the setpoint temperature in the two test cells and the energy savings thanks to the integration
772 of the bifacial BIPV facade calculated taking the test cell 3 results as reference. The total energy
773 consumption is the sum of energy consumptions (in absolute values) for heating and cooling on a
774 defined period.

775

776 *Table 7: Measured cumulated monthly and period energy consumptions for heating and cooling and total energy*
777 *consumption needed to maintain the setpoint temperature in the reference test cell 3 (non-insulated concrete wall)*
778 *and in the test cell 4 with the bifacial BIPV facade (in kWh) and calculated energy savings (relative difference of*
779 *total energy consumptions in %) from December 2018 to December 2019.*

	Prototype energy consumption for Heating (kWh)	Reference energy consumption for Heating (kWh)	Prototype energy consumption for Cooling (kWh)	Reference energy consumption for Cooling (kWh)	Prototype total energy consumption (kWh)	Reference total energy consumption (kWh)	Relative difference of total energy consumptions (%)
December 2018	25	174	9	8	34	182	-81
January 2019	45	409	3	0	48	409	-88
February 2019	27	269	2	0	29	269	-89
March 2019	12	160	2	1	13	160	-92
April 2019	9	59	1	1	10	60	-83
May 2019	6	42	41	26	47	68	-31
June 2019	0	1	145	226	145	227	-36
July 2019	4	3	133	279	137	282	-51
August 2019	0	1	120	256	120	257	-53
September 2019	1	2	83	142	84	143	-41
October 2019	1	3	41	36	42	39	8
November 2019	9	131	3	2	13	133	-90
December 2019	12	126	2	1	14	127	-89
Total values	158	1387	632	1020	636	1963	-68

780

781 Results of table 7 indicates that the integration of the developed bifacial BIPV facade permitted a
782 reduction of the total energy consumption up to 92% (reached in March 2019). In warm season, the
783 total energy consumption was comprised between 60 kWh (in March 2019) and 282 kWh (in July
784 2019) in the reference test cell (test cell 3) and between 10 kWh (in March 2019) and 145 kWh (in

785 June 2019) in the test cell 4. The reduction of energy consumption in the test cell 4 was between -83%
 786 (in April 2019) and -31% (in May 2019) compared to the test cell 3 results.

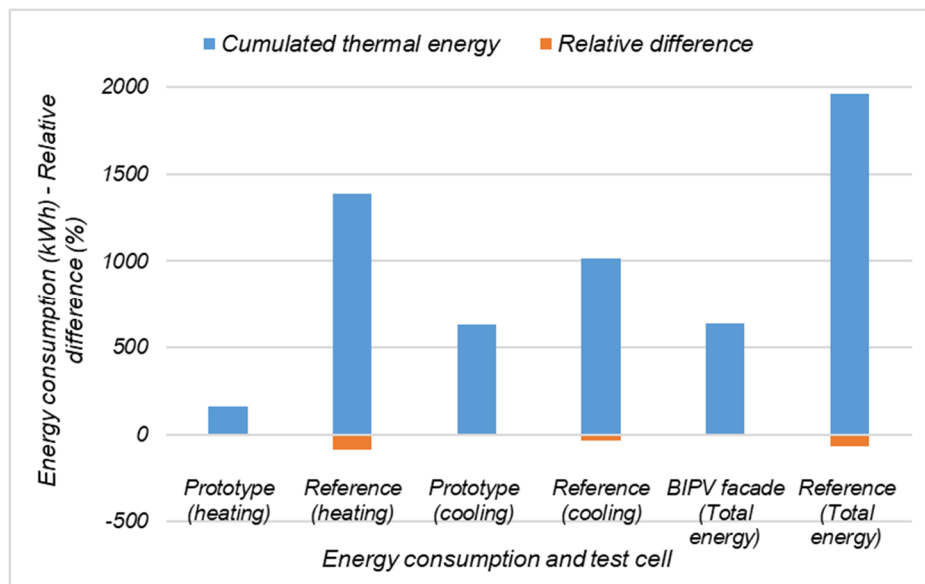
787 In cold seasons, the total energy consumption was between 39 kWh (in September 2019) and 409
 788 kWh (in January 2019) in the reference test cell and between 13 kWh (in November 2019) and 48 kWh
 789 (in January 2019) in the test cell 4. The decrease of energy consumption in the test cell 4 was
 790 between -92% (in March 2019) and 8% (in October 2019) compared to the test cell 3.

791 The positive relative difference of total energy consumption noted in October 2019 (of 8%) could be
 792 due to the test cell 4 internal door openings (see figure 5 a) leading to an increase of energy
 793 consumption for cooling.

794 Then, results show that the BIPV system developed has a higher impact on the test cell total
 795 energy consumption in cold season (energy savings between 81 and 92%) and especially on the
 796 energy consumption for heating compared to the reference test cell.

797
 798 Figure 16 provides the cumulated total energy consumption and energy consumptions for heating and
 799 cooling in the two test cells and the relative differences of energy consumption in each case from
 800 December 2018 to December 2019.

801



802
 803 Figure 16: Cumulated values of the total energy consumption and energy consumptions for heating and cooling
 804 needed to maintain the setpoint temperature in the test cell 3 (reference) and in the test cell 4 (with the BIPV
 805 facade) (in kWh) and relative differences of energy consumption (in %) from December 2018 to December 2019.
 806

807 The cumulated total energy consumption on the whole period was of 636 kWh in test cell 4 and of
 808 1963 kWh in the reference test cell corresponding to a reduction of 68% (see table 6 and figure 16).
 809 More precisely, the cumulated energy consumption for heating was of 158 kWh in test cell 4 and of
 810 1387 kWh in the test cell 3, corresponding to a reduction of nearly 89% after the BIPV facade
 811 integration. The cumulated energy consumption for cooling was of 632 kWh in test cell 4 and of 1020
 812 kWh in the test cell 3, corresponding to a decrease of nearly 38% (See figure 16). The values obtained
 813 confirmed that the solar solution designed permits to get closer to the targeted reduction of energy

814 consumption for heating of 60%. These high energy savings values after the BIPV facade integration
815 could be limited in case of heat losses through the other test cell walls.

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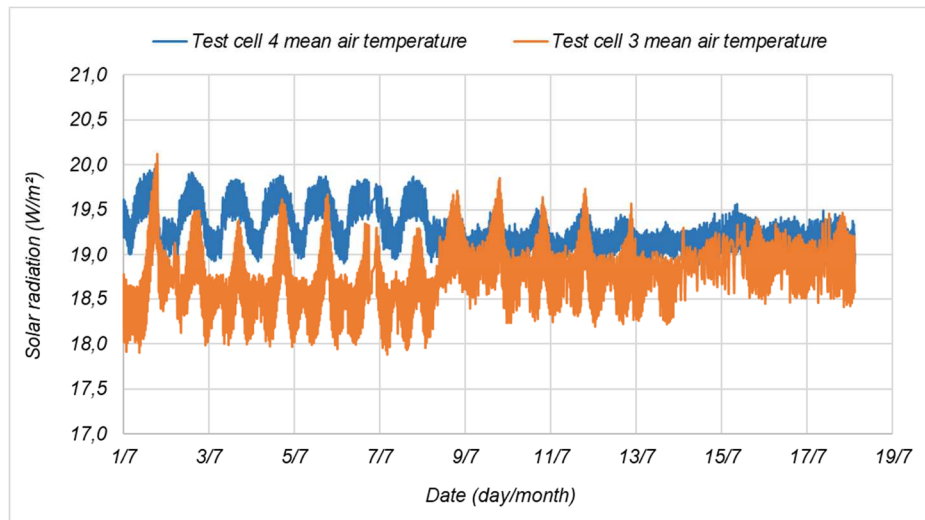
817 7.2. Analysis of the impact of the bifacial PV modules on the indoor air temperature on a daily base

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819 The impact of the integration of the bifacial PV modules on air temperature in the test cell was also
820 analyzed on a daily base during a month in cold season and a month in warm season in order to
821 explain the huge reduction of building energy consumption.

822 Figure 17 presents the two test cells mean air temperature profiles in July 2019 (warm month) (see
823 figure 17 a) and in January 2019 (cold season) (see figure 17 b).

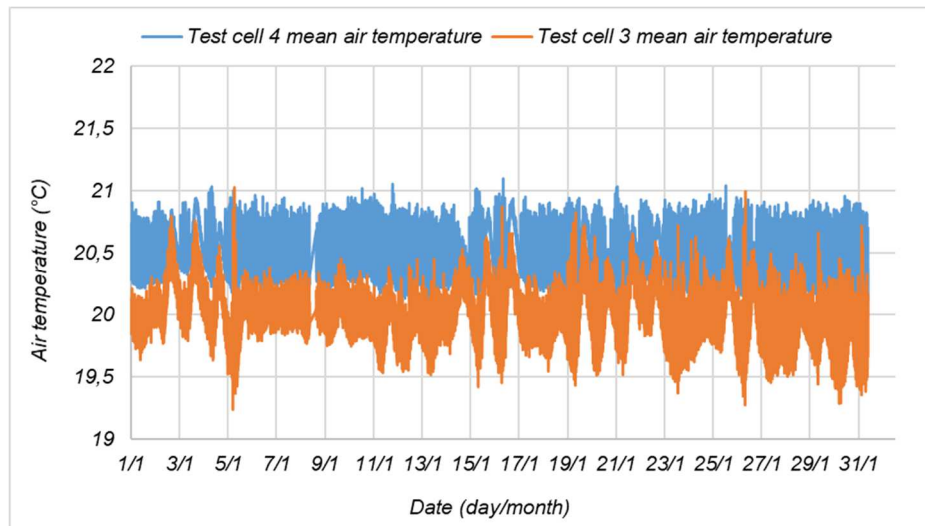
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(a)



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(b)

829 Figure 17: Indoor air temperatures profiles of the test cells 3 and 4 in July 2019 (a) and in January 2019 (b).

830

831 In July 2019, figure 17 a shows that most of the time, the air temperature in the test cell 3
832 (reference) is slightly lower than the air temperature in the test cell 4. The difference of air

833 temperatures taking the test cell 3 as reference is comprised between -0.41°C and 1.6°C with a mean
834 value of 0.54°C . (See figure 17 a)

835 In January 2019, similar observations can be made (see Figure 17 b). The difference of air
836 temperatures is between -0.63°C and 1.4°C with a mean value of 0.45°C . (See figure 16 b)

837 These differences of air temperatures show that the integration of the BIPV system leads heat rise
838 in the test cell 4, reducing heat losses through the initial non-insulated concrete facade (as expected
839 for the test cell 3). Thus, the difference of total energy consumption between the two test cells (see
840 table 7 and figure 16) could be explained by the lower heat exchanges between the test cell 4 air
841 (convective and radiant) temperature and its BIPV facade compared to heat exchanges between the
842 test cell 3 air temperature and its reference non-insulated concrete facade. Indeed, in the test cell 4,
843 heat exchanges through the facade are mainly influenced by the insulation layer, by the albedo effect,
844 by the fiber concrete panels cooling thanks to stack effect especially in warm season (reducing energy
845 consumption for cooling) and by a greenhouse effect in cold period in the insulated air gap (reducing
846 energy consumption for heating). In the test cell 3, the heat stored in the facade is partially transferred
847 to indoor environment by conduction, convection and radiation.

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850 **8. Conclusion**

851 The innovative bifacial photovoltaic facade element was described. Then, the nearly one year
852 outdoor tests performed on the south-oriented facades of two full- scale test cells at Le Bourget du Lac
853 integrating eight photovoltaic prototypes and a reference non-insulated concrete wall were presented
854 focusing on the monitoring system description and on the analysis of thermal, electrical, energy
855 consumption and weather data on daily, monthly and annual bases.

856 Based on two instrumented photovoltaic modules, thermal results mainly highlighted daily mean
857 temperatures between -4.4°C in January 2019 and 68.3°C in September 2019 and an important
858 monthly thermal gradient up to 7°C nearly, especially due to the combined impacts of stack effect and
859 site albedo.

860 Moreover, the photovoltaic field produced a cumulated electrical energy of 63.8 kWh/m^2 corresponding
861 to a performance ratio of 0.73 and a mean annual efficiency of 6.3% from December 2018 to
862 December 2019, which is satisfactory for a façade integrated system. Close cumulated electrical
863 performance in cold period (of 29.4 kWh/m^2) and in warm period (of 31.5 kWh/m^2) were observed and
864 could be explained by the rear side additional production of the bifacial PV modules.

865 Then, the comparison of temperatures distribution on the internal coatings and the outside of the
866 two test cells facades using thermal images showed that the bifacial photovoltaic facade permits a
867 relevant reduction of heat transfers through the concrete wall at low and high solar radiation levels.

868 Finally, the comparison of total energy consumption (for heating and cooling) of the two tests cells
869 highlighted that the photovoltaic prototype integration permitted an important energy saving up to 92%,
870 especially in cold season. The cumulated total energy consumption was of 636 kWh in the test cell
871 with the solar facade and of 1963 kWh in the reference test cell corresponding to a reduction of 68%
872 on the whole period. The comparative analysis of indoor air temperatures highlighted that the facade
873 integration of the bifacial photovoltaic system seems to permit a management of heat transfers

874 through the initial test cell non-insulated concrete wall. This leads to a reduction of energy
875 consumption for heating and cooling mainly through the wall insulation, the albedo effect, the fiber
876 concrete panels cooling by stack effect in warm season and a greenhouse effect especially in cold
877 period in the insulated air gap. Nevertheless, these important energy savings could be reduced by
878 heat losses through the other test cell walls.

879 Results obtained in this work contribute to validate the relevance of the integration of bifacial
880 photovoltaic modules into building envelope and thus, to encourage their use in the framework of solar
881 projects, although the less optimal operating conditions for the rear side electrical energy production.

882 As further studies, the tested configuration will be integrated into an office building in order to
883 demonstrate its performance in real conditions during nearly one year.

884

885

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889 Commission and by the LIFE program under project reference LIFE14 CCM/FR/000954.

890

891 **Nomenclature**

892

Symbols

AC	Alternative current
BIPV	Building integrated photovoltaic module
C _p	Electrical performance loss coefficient (-)
dT _j	Absolute difference of temperatures of layer j (°C)
E _{ac}	Electrical energy produced in AC (Wh)
E _i	Incident solar energy (Wh/m ²)
E _{pvmf}	Electrical energy production of the monofacial PV modules (Wh)
EVA	Ethylene vinyl acetate
G _i	Incident total solar radiation (W/m ²)
G _{STC}	Incident solar radiation in standard tests conditions (STC)
HET	Heterojunction photovoltaic module
I _{sc}	Short circuit current (A)
NOCT	Nominal operating cell temperature conditions
P _{max}	Nominal power installed (Wp)
P _{pvmf}	Electrical power production of the monofacial PV modules (W)
P _{rac}	Performance ratio after inverter (-)
PV	Photovoltaic module
S _{pv}	Surface of the PV field (m ²)
STC	Standard tests conditions

T _i	Temperature of i material (°C)
V _{oc}	Open-circuit voltage (V)
Y _f	Final yield (kWh/kWp)

Greek

η_{pv}	Electrical efficiency of the photovoltaic module (%)
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Subscripts

mean	Mean value
PV, pv1	Photovoltaic
pv3	Photovoltaic module 3
pv5	Photovoltaic module 5
ref	Reference value
STC	Standard tests conditions

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