Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Départmenet fédéral de l'environnement, des transports,
de l'énergie et de la communication DETEC

Ofiice fédéral de l'énergie OFEN

Final Report October 31, 2011

Building Integrated Photovoltaics - Thermal Aspects

Low Energy House for Testing BIPV Systems

Client:
Federal Office of Energy OFEN
Forschungsprogramm Energie in Gebäuden
CH-3003 Bern
www.bfe.admin.ch

Co-financing:
Federal Office of Energy, CH-3003, Bern
SUPSI, CH-6952, Canobbio

Sender:
ISAAC – DACD – SUPSI
Swiss BiPV Competence Centre
Campus Trevano
CH-6952, Canobbio
www.isaac.supsi.ch
www.bipv.ch

Authors:
MSc. Chatzipanagi Anatoli, Swiss BIPV Competence Centre, ISAAC – DACD - SUPSI
Dr. Frontini Francesco, Swiss BIPV Competence Centre, ISAAC – DACD – SUPSI
Ing. Kim Nagel, Swiss BIPV Competence Centre, ISAAC – DACD – SUPSI

Area responsible of the SFOE: Dr. Charles Filleux
Program manager of the OFEN: Mr. Andreas Eckmanns
Number of contract and project of the OFEN: 154147 / 103155

INDEX

ABSTRACT

PV industries offering products that can be integrated as building materials (BiPV product) represent so far a niche but a promising market. In Switzerland, according to a study of the International Energy Agency (IEA), the potential of PV installed in well-oriented roofs and facades in Switzerland represents 35% of the annual electricity demand. At the moment, only a few studies have been carried out in order to assess the interaction between the fastening systems or the building component and the PV modules. This fact may represent a barrier for the PV industry but also for the building industry, which has yet to gain confidence in these new materials.

This project analyzed these innovating products. In order to define their electrical and thermal characteristics a Building integrated PV (BiPV) test stand was built at SUSPI-ISAAC and 22 modules were monitored for one year and the thermal characteristics (U-value and g-value) were measured at the EMPA laboratory. In this Final report the main results are presented.

It was found that the performance of BiPV modules is influenced by the combination of the:

type of integration,

inclination,

temperature coefficients of the modules and

annealing effects.

The thermal characteristics of the modules exhibited satisfactory values and can be used in building construction in order to achieve the Minergie® standard.

However, in addition to the aspects above, also the

- lifetime and long-term degradation of the modules,
- aesthetics and cost
- must be taken into consideration.

1. Project goals

During this project, different module technologies of different mounting/integration solutions at different inclinations were monitored as far as their electrical and thermal behavior is concerned. Throughout this monitoring, the main aspects of investigation were :

the acquisition of knowledge regarding the temperature effect on the electrical performance of BIPV modules,

the investigation of the influence of the inclination (façade, pitch and flat roof),

the investigation of the influence of the different substrates and composition (glass, insulating material, metal sheet) on the electrical properties of BIPV modules,

the acquisition of knowledge regarding the thermal characteristics (g and U values) of semi-transparent PV modules when integrated in double glazing unit (DGU),

the knowledge sharing with the industry sector and last but not least

the diffusion of results.

The objectives were reached with a small delay due to the large extend of the data to be processed and also due to the fact that the thermal characteristics of the modules measured at EMPA needed more time than expected.

This work was already presented at the 26th EUPVSEC in Hamburg (07.09.2011), as well as at the Solar Power UK in Birmingham (27.10.2011) and will be part of other scientific publications.

2. Work performed and results achieved

2.1. Introduction

As Building Integrated Photovoltaics (BiPV) is getting more popular, it is expected that in the future this sector of the PV market will exhibit an increase. However, at the moment, few studies have been carried out concerning the behavior of BiPV products as well as their interaction with the building.

This project aims to the analyze the electrical and thermal behavior of different technologies of BiPV products, with different types of integration and different inclinations.

The project, hence also the monitoring period, lasted 1 year (01.04.2010 – 31.03.2011).

The modules which were part of the project were 22 in total. Due the request of an industrial partner to have copyright on the obtained results, in this report the results of only 15 will be presented. Two of the modules are high efficiency c-Si SunPower modules, one of which has a black back sheet and the other a white back sheet. The later was used as a reference module for the inter-comparison of the modules.

2.2. Identification of modules

Table 1 presents the nominal stabilized power of the modules given by the manufacturer (PN) and the nominal power measured at ISAAC after the conclusion of the project (PISAAC_FINAL after one year exposure).

The value of power selected for the calculation of the energy production, final yield and performance ratio is the PISAAC_FINAL and that is because it is the only value taking into consideration the degradation of the modules after 1 year of outdoor exposure.

Table 1: Description / Specification of modules.

ISAAC Label	Technology	P_N [W]	P_{ISAAC_final} [W]	ΔP [%]	Mounting Type	Inclination	Transparency
BIPVTP/1	a-Si/a-Si	52	60.98	17.3	Integrated (IG)	30°	Yes
BIPVTP/2	a-Si/a-Si	52	59.46	14.4	Integrated (IG)	90°	Yes
BIPVTP/3	a-Si/a-Si	78	82.01	5.1	Ventilated (V)	90°	No
BIPVTP/9	c-Si	230	227.47	-1.1	Ventilated with white back sheet (V, wh) Reference Module	30°	No
BIPVTP/10	c-Si	225	217.45	-3.4	Ventilated with black back sheet (V, bk)	30°	No

BIPVTP/11	a-Si	17.8	18.80	5.6	Insulated black metal (INS, bk met.)	0°	No
BIPVTP/12	a-Si	18.5	20.07	8.5	Insulated white metal (INS, wh met.)	0°	No
BIPVTP/13	a-Si	19	19.70	3.7	Ventilated Al sheet (V, Al)	0°	No
BIPVTP/14	a-Si	19	20.09	5.7	Ventilated Cu sheet (V, Cu)	0°	No
BIPVTP/15	a-Si	18.6	19.49	4.8	Ventilated Zn sheet (V, Zn)	0°	No
BIPVTP/16	a-Si	18.6	19.73	6.1	Insulated white membrane (INS, wh mem.)	0°	No
BIPVTP/17	a-Si	18.6	18.69	0.5	Insulated black membrane (INS, bk mem.)	0°	No
BIPVTP/18	a-Si/a-Si	40	42.07	5.2	Ventilated (V)	90°	No
BIPVTP/19	a-Si/a-Si	26	27.38	5.3	Integrated (IG)	30°	Yes
BIPVTP/20	a-Si/a-Si	26	26.95	3.6	Integrated (IG)	90°	Yes
BIPVTP/21	c-Si	175	176.44	0.8	Integrated (IG)	30°	Yes
BIPVTP/22	c-Si	175	176.29	0.7	Integrated (IG)	90°	Yes

Table 1 shows the stabilized power, as given by the manufacturers in comparison with the indoor measured power after one year of outdoor exposure. After the first year the initial degradation is expected to be more or less completed for all amorphous technologies. The indoor measurement has been performed in summer, when the amorphous silicon modules are likely to be close to their maximum performance due to the annealing process within the precedent months. It has been chosen to use this measurement (PISAAC_final) as a reference for the evaluation of the later module performance inter-comparison, as being the measurement closest to the 'stabilized' power. Unfortunately it was not possible to dismantle and measure the modules more frequently, so to have a better idea about the seasonal variations.

As expected all amorphous technologies show a positive ΔP, with values which vary from 3.5% to 17% in dependence of the type of technology and the temperatures reached within the different integration solutions. The crystalline silicon technologies lie all in the range of the declared tolerances.

When looking in more detail to the amorphous technologies, the BIPVTP/1 and BIPVTP/2 modules (both of them integrated) exhibit a significantly higher power of about 15-17%, whereas the same module but ventilated at 90°C (BIPVTP/3) of only 5%. The rest of the a-Si/a-Si modules showed a similar behavior, but with a less pronounced difference between ventilated and integrated modules. For the flexible a-Si modules the spread to the manufacturer data was between 0.5% and 8.5%.

2.3. Bipv-temp stand description

The test facility realized on the roof of ISAAC (fig. 1) consists of 3 different parts. One part is the Low Energy House, which is constructed with respect to the building construction standards as well as the Minergie label. In order to respect the above standards, an air-conditioning system inside the house was used to maintain the temperature around 21-22°C. In addition, a mechanical fan ensured the temperature uniformity of the internal space. On the façade (90°) and on the roof (30°) transparent modules of different technologies were mounted as integrated PV modules. The transformation of the standard modules (as provided by the manufacturers) was performed by the companies Galvolux and Verres Industriel.

The second part of the test facility is a sloped roof (30° from the horizontal and a vertical façade 90° from the horizontal) where standard modules were mounted in a naturally ventilated way. On the 30° were also mounted the 2 SunPower modules (one with a white back sheet and one with a black). The SunPower module (BIPVTP/9) with the white back sheet was chosen as a reference module for the inter-comparison of the different modules that took part in the project. It has to be noted that this is a high efficiency crystalline module.

The last part of the test stand is the roof (0°), which is not part of the Low Energy House and where modules on different insulating membranes and metal sheets were mounted.

Figure 1: BiPV test stand: external and internal view.

In Annex 10.1, further photographs of the testing stand can be found.

2.4. Weather conditions during the monitoring time-frame

A significant factor that influences the energy production of a module is the amount of insolation reaching its surface. The amount of sunlight reaching the modules is influenced by the sky conditions (clear or cloudy day), the sun's height (season dependent) and the albedo effects.

In order to measure the insolation at the different inclinations of the test facility, 3 pyranometers were mounted at 0°, 30° and 90° inclination (see also right picture in fig. 1).

Fig. 2 presents the daily average insolation values for the 3 different inclinations of the test facility.

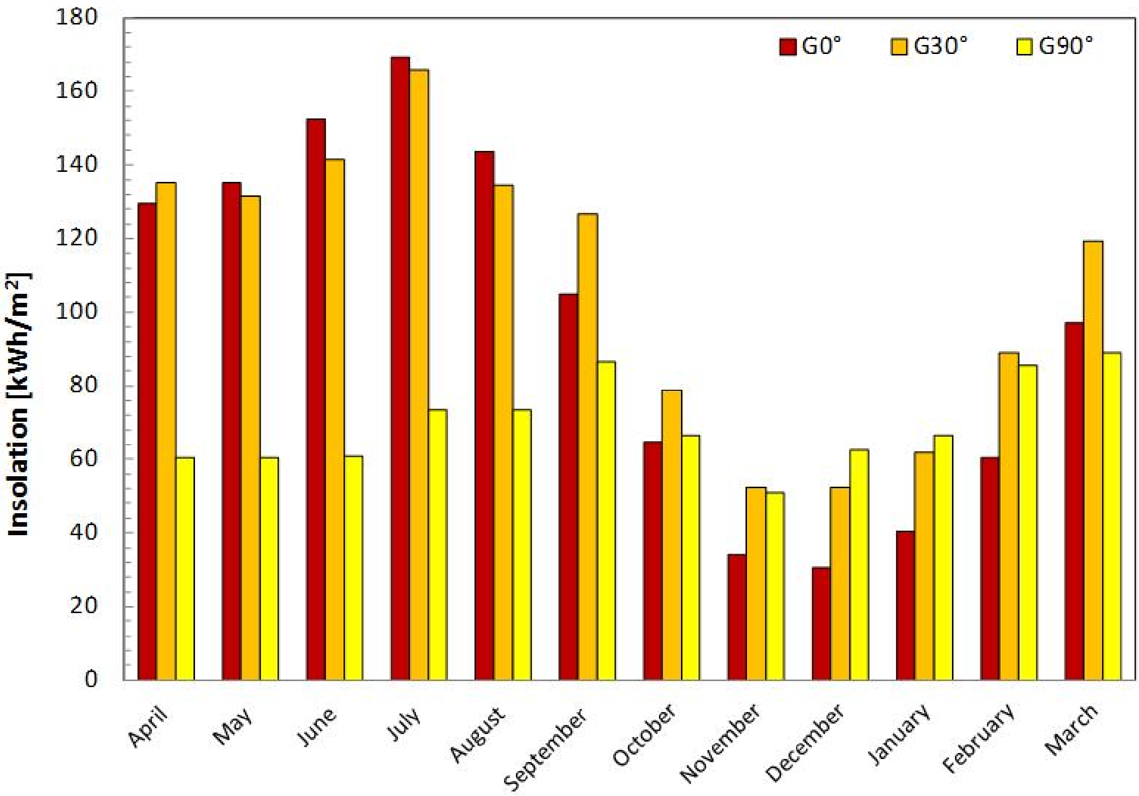


Figure 2: Daily average insolation for 0°, 30° and 90° inclination for the total period of monitoring.

According to the figure above, during the spring and summer months (March – September) the inclinations of 0° and 30° are more favorable in terms of insolation, whereas the 90° receives less sunlight. The reason for this is mainly that the sun during this period is high in the sky. From May to August, the inclination receiving more sun is the one of 0°.

After September, when the sun is getting lower in the sky, the sunlight reaching the 0° inclination is decreasing and at the same time 90° inclination is favored.

As seen by the medium values for the whole monitoring period, the best inclination in terms of the highest insolation values is the 30°, followed by the 0°, as expected.

For the evaluation of the results 351 days of monitoring (14 days were eliminated due to data acquisition problems of irradiance) were taken into consideration. However, it is useful to group the days into 3 "type of day" categories. In this way it is possible to link the results with the available insolation during the monitoring period. These are clear sky days, cloudy sky days and overcast sky days. This categorization was done according the Perez's clearness index (Annex 10.2). Table 2 presents the number of clear, cloudy and overcast days during the monitoring year. In addition, the percentage of insolation of each type of day for the different inclinations is shown.

Table 2: Evaluation of days of monitoring with dependence on the irradiance

Day Type	Days	G_0°	G_30°	G_90°
Clear	123	47.9%	52.3%	56.7%
Cloudy	138	46.5%	43.2%	39.8%
Overcast	90	5.6%	4.5%	3.5%
Total	351	100%	100%	100%

It is clear from the table above that the majority of the days during the outdoor exposure of the modules were clear and cloudy days and for those days the insolation was the 95% of the total insolation during the year for all inclinations.

2.5. Indoor measurements

Prior as well as after the mounting/integration of the modules on the test facility, STC power measurements were performed at ISAAC. Moreover, at the end of the project, additional measurements like Measurement of Temperature Coefficient (TCO), Performance at different Irradiance levels (GCO) and Performance at Low Irradiance (PL) were carried out.

The indoor measurements were performed with a pulsed sun simulator (better than IEC class A). The measurements of all modules are ISO 17025 accredited by the Swiss Accreditation Service (SAS). The module under test has been measured with a spectral adapted reference cell for each module technology. This reduces the measurement error due to a lower spectral mismatch between module and reference cell.

The temperature coefficients of the modules was obtained by performing the TCO measurement. According to it, the modules were measured at 1000 W/m^2 and between 25°C and 65°C.

For the GCO measurements, the modules were measured at different irradiance levels between 100 W/m^2 and 1000 W/m^2 at 25°C.

2.6. Data monitoring

The recorded data during the one year (April 2010 – March 2011) of this project were the:

1) I-V curves of each module
2) electrical parameters of each module (V_m, I_m)
3) irradiance at 0°, 30° and 90°
4) temperature at the back of each module (T_{bom})
5) internal temperature of the Low Energy House (east, centre, west)
6) ambient temperature

All data above were registered every minute apart from the I-V curves, which were registered every five minutes.

In order to ensure the availability and accuracy of the acquired data, an automatic alarm system for errors was implemented [1]. These errors were grouped concerning general errors, errors related to the modules, to the MPPTs, to the irradiance and to the temperature. The implementation of this alarm system helped with the better evaluation of data as well as with the prompt correction of eventual problems.

Apart from the excluded days for which the data acquisition of irradiance values was inaccurate, there are also some days during the monitoring period that were excluded due to other errors encountered like the ones mentioned above. The prompt resolution of the problem for these days was not possible.

2.7. Analysis

2.7.1. Performance analysis

Energy production

When having to deal with the energy produced by BiPV modules, it is better to express it as energy production per square meter (kWh/m^2). That is because this quantity is important for architects and also consists a standard unit for the analysis of costs and energy needs.

Fig. 3 presents the energy production per square meter for all the modules (for the whole monitoring period). The calculation of the values presented in the following figure was performed by using the STC power measurement performed at ISAAC after the dismounting of the modules P_{ISAAC_final}.

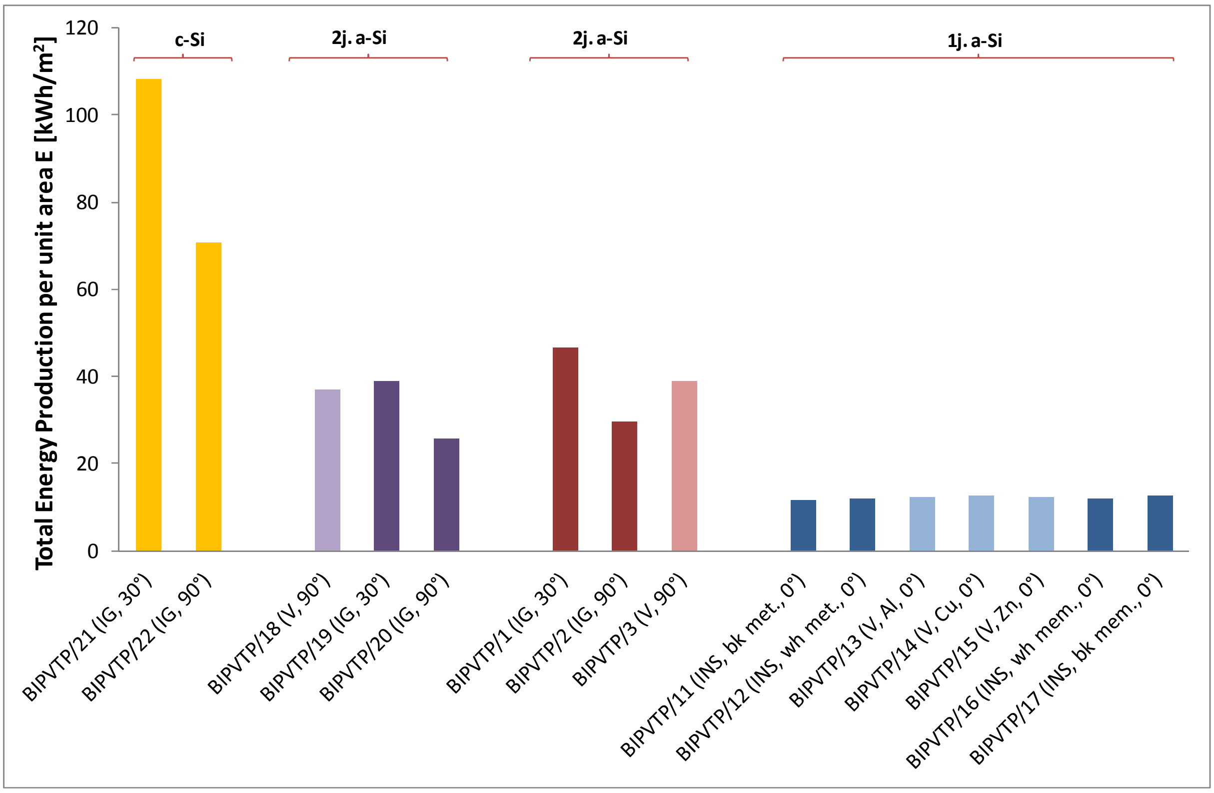


Figure 3: Total energy production per unit area for all the modules for the whole period of monitoring.

According to fig. 3, the c-Si modules have produced more energy per square unit area for the whole year. More particularly, the one integrated at 30° produced 40kWh/m^2 and that is because of its more favorable inclination. The two a-Si/a-Si modules that were integrated at 90° (BIPVTP/20 and BIPVTP/2) produced less energy than the rest of a-Si/a-Si modules whereas the most energy produced for this technology was from the integrated at 30° (BIPVTP/19 and BIPVTP/1). Ultimately, as far as the flexible a-Si modules on different membranes and sheet materials are concerned, they all produced approximately the same energy per square unit area.

Performance ratio

The performance ratio (PR) facilitates the comparison of modules in different locations or at different inclinations. It is expressed by dividing the final yield with the normalized irradiation. Since the performance ratio calculation includes the final yield value, it is also affected by the used power value [2]. The power that was used is again P_{ISAAC_final}.

Figure 4 presents the difference in Performance Ratio (ΔPR) of the modules for the monitoring period.

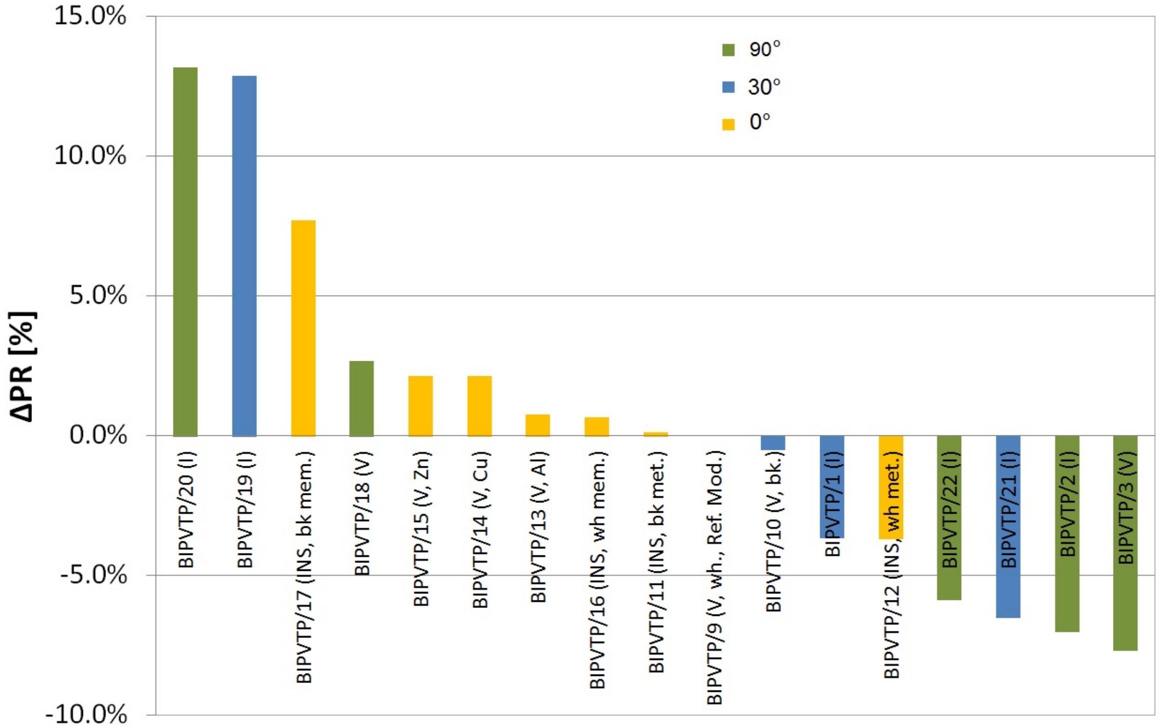


Figure 4: Difference in performance ratio for all the modules with reference to the Sunpower module for the whole period of monitoring.

As observed in fig. 4, there are two groups of a-Si/a-Si modules created. One is that of the two best performing modules on the graph (BIPVTP/20 and BIPVTP/19), which exhibit a higher performance ratio than the reference module of about 13%. The other group is that of the least performing modules on the graph (BIPVTP/2 and BIPVTP/3) that exhibit a lower performance ratio than the reference module of about 7%. According to the GCO measurements performed, it was found that the modules of the first group have a very good efficiency also at low irradiance levels and hence take advantage of more sunlight. In addition, apparently the annealing effect on them was stronger than that on the modules of the second group. In fact, the BIPVTP/18 (which is of the same technology) has demonstrated a lower performance ratio and that is due to the fact that is ventilated and lower temperatures were reached.

The two c-Si modules showed a lower performance ratio than the reference module of around 6% and that is because higher temperatures were reached for the BIPVTP/21 and BIPVTP/22 which were integrated at 30° and 90° whereas the reference module was mounted as ventilated at 30° (temperature coefficient effect).

When observing the flexible a-Si modules, it can be seen that the one on the black membrane has a performance ratio of 7-8%, while the ones on different materials have a performance ratio in the range of 1-3%. It is believed that this is due to the fact that the module on the black membrane was integrated as insulating element on the roof and moreover because of its color (slightly higher working temperatures).

2.7.2. Temperature analysis

A very important parameter that influences the behavior of modules is the cell temperature (during working time). The fact that the working temperature of an integrated module is higher than that of a mounted one, is crucial to investigate how temperature affects the performance of a BiPV module.

As mentioned in the data monitoring section, the temperature at the back of all modules was monitored during the one year of their outdoor exposure. However, this was not the actual working temperature of the modules. In fact because of the transformation of the modules into double insulating glass filled with argon, it was not possible to place a PT100 behind the cell but a PT100 was installed at the rear surfaces of the glasses. Therefore, the calculation of the Equivalent Cell Temperature (ECT) was performed according to IEC 60904-5 Standard.

Figures 5 and 6 present the calculated maximum ECT (ECT_{max}) of a few modules and in addition, the maximum ambient temperature (T_{amb_max}) is plotted.

According to figure 5 and as expected, the integrated modules exhibited higher working temperatures than the ventilated ones for the same inclination, at 90°.

For the ventilated modules, temperatures were in the range of 45°C-55°C whereas for the integrated ones the range is 55°C-75°C.

As observed, the working temperatures of the modules have a smaller variation throughout the year in comparison to the ambient temperature.

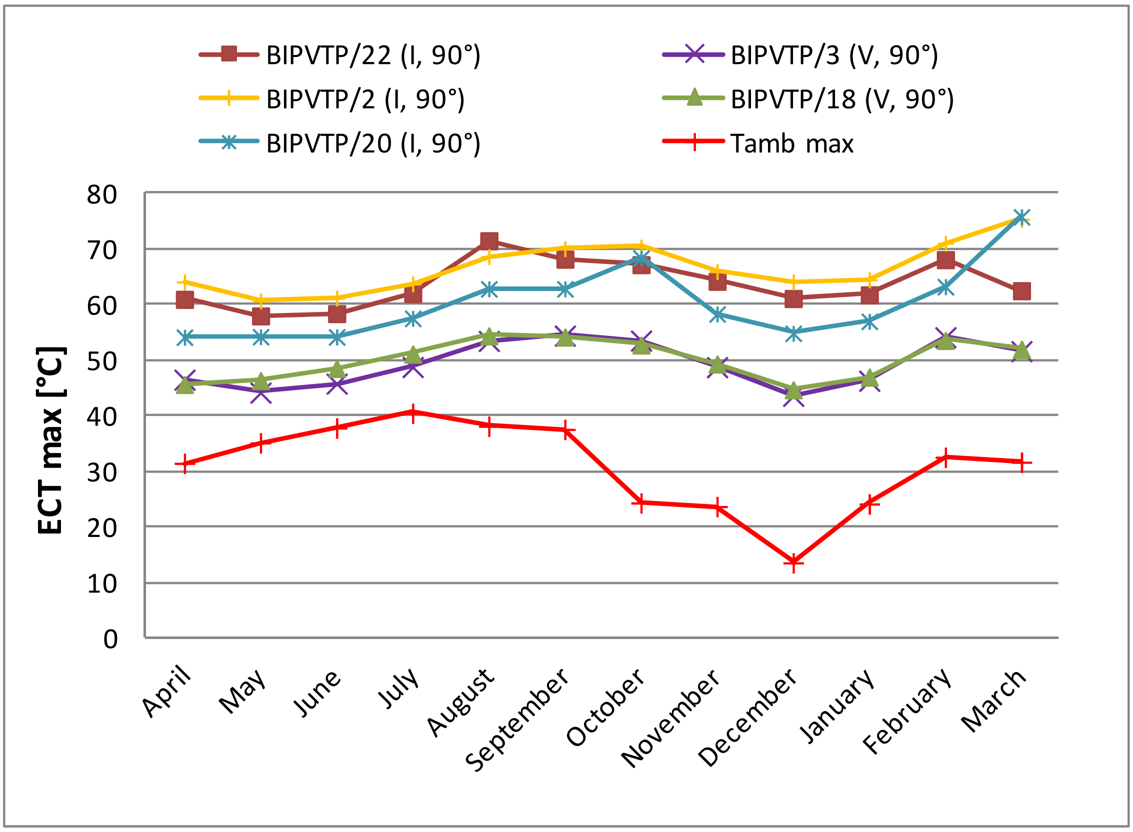


Figure 5: Maximum calculated Equivalent Cell Temperature (ECT_{max}) and maximum ambient temperature (T_{amb_max}) for some modules for the whole period of monitoring.

From fig. 6, it is evident that the integrated modules at 30° exhibit a greater variation of temperatures throughout the year than the rest. The range is from 48°C up to 71°C (for

BIPVTP/19) and 81°C (for BIPVTP/21). The integrated at 90° modules show a variation of around 15°C.

The ventilated module at 90° on the other hand exhibited the lowest temperatures throughout the monitoring period and never exceeded 52°C.

Also in this figures, it can be seen that the working temperatures of the modules have a smaller variation throughout the year in comparison to the ambient temperature.

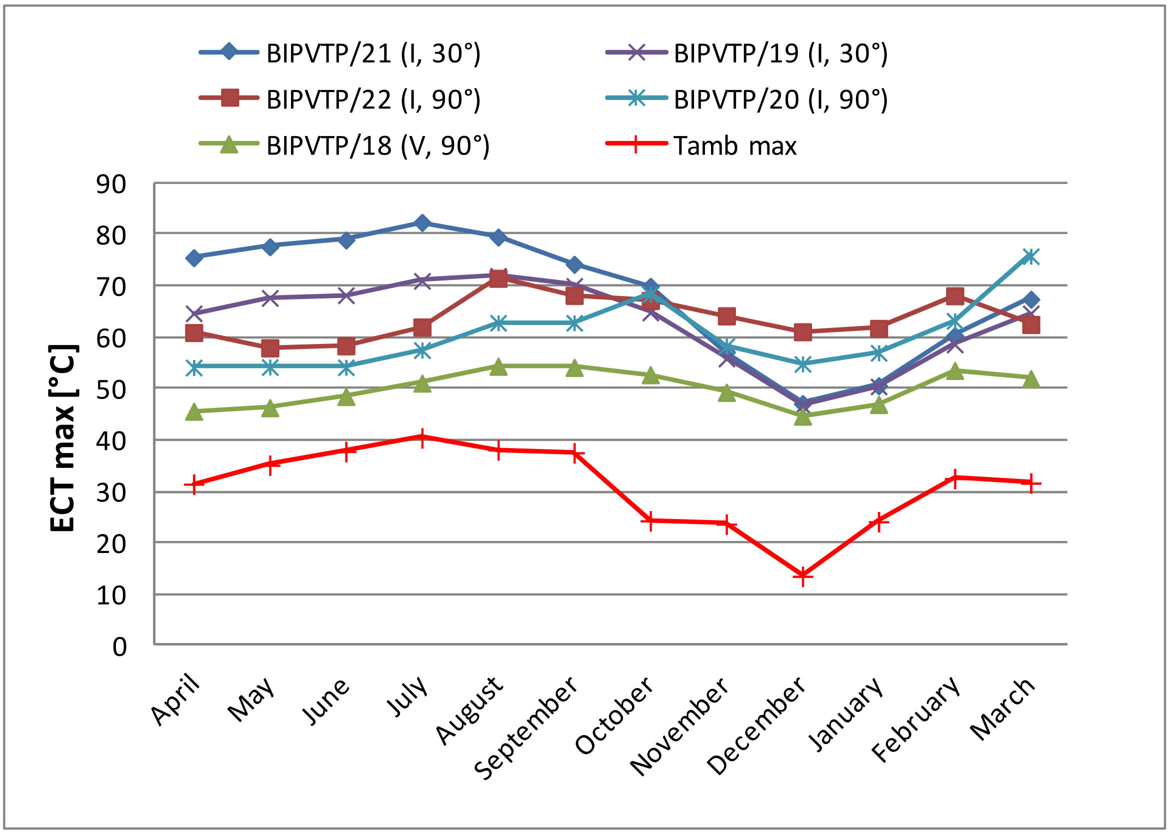


Figure 6: Maximum calculated Equivalent Cell Temperature (ECT_{max}) and maximum ambient temperature (T_{amb_max}) for some modules for the whole period of monitoring.

2.8. THERMAL CHARACTERIZATION

In order to empirically assess the thermal characteristic of the BIPV windows (U-value and g-value), four modules were tested at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) located in Duebendorf (Switzerland). Measurements of the solar gains through the windows were performed in a calorimetric outdoor test facility (test cell) (fig. 7) according to the procedure described and validated in [3] and [4].

Figure 7: Solar Radiation calorimeter at EMPA.

The U-value was measured in a large guarded hot box facility (fig. 8).

Test cells provide a unique environment for empirical validations and lie between a carefully controlled laboratory environment and an actual building. They have the advantage that the inside test cell boundary conditions can be well controlled while also maintaining an environment that is similar to an actual office space envelope [4]. These tests were performed during June and August 2011.

Table 3 resumes the results of the g-value measurements performed only for the two (BIPVTP/1 and BIPVTP/21) of the four modules tested.

Table 3: g-value measurement.

Data	BIPVTP/21	BIPVTP/1
Technology	c-Si	a-Si/a-Si
Area [m2]	1.62	1.23
g-value	**0.153**	**0.120**

The g-value on the other hand is changing according to the windows and PV cells design. It is less than 0.2.

The BIPVTP/21 module (c-Si), as expected, has a slightly higher g-value than the BIPVTP/1 (which has an homogenous transparency), due to the space between the crystalline cells (lower values can be reached with more opaque modules).

Table 4 resumes the results of the U-value measurements performed for the same two modules in the hot chamber (figure 8).

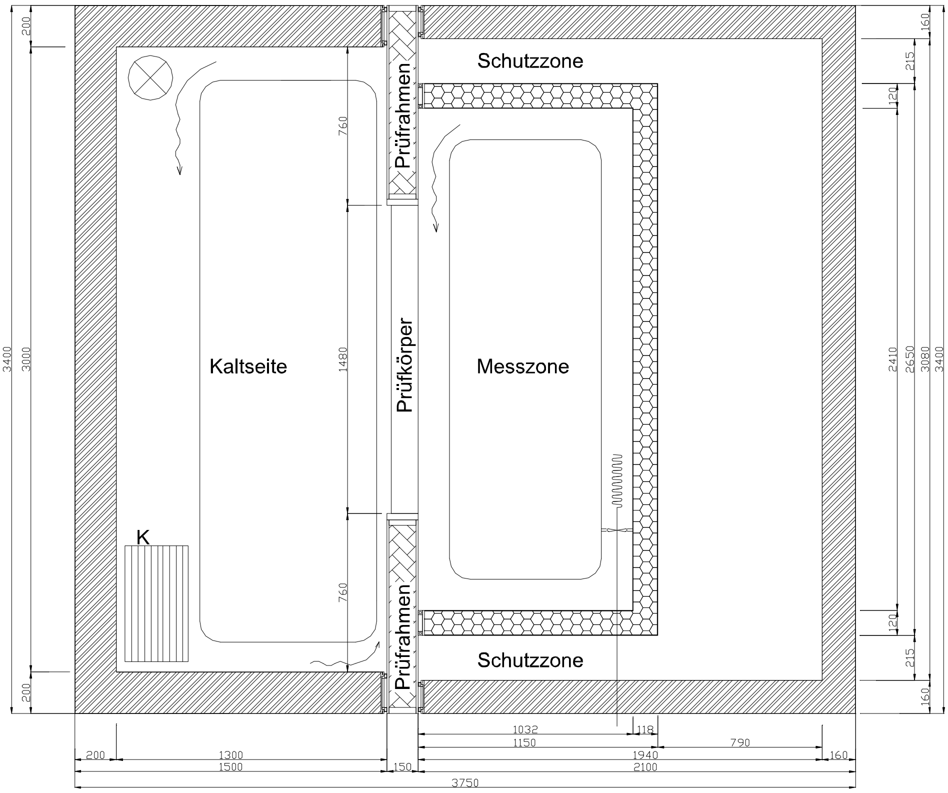


Figure 8: Schematic vertical section of the U-value chamber at EMPA laboratories.

The modules have a thermal conductivity of 1.05 W/m^{2}K (BIPVTP/1) and 1.1W/m^{2}K (BIPVTP/21) that is due to the fact that they all have a double glazing unit filled with argon.

Table 4: U-value measurement.

Data		BIPVTP/21	BIPVTP/1
Glass			
- centre of the glass θsi, glazing	[°C]	20.23	20.36
- centre of the glass θse, glazing	[°C]	5.16	5.00
- Temperature difference	[K]	15.07	15.37
Heat flux ΦG	[W/ m^2]	20.48	19.60
Thermal resistance of the glass Rg	[m^{2}K/W]	0.75	0.78
Standard Heat transfer coefficient Rs,st hi=7.7 [W/(m^{2}K)] he=25[W/(m^{2}K)]	[m^{2}K/W]	0.17	0.17
Total Resistance	[m^{2}K/W]	0.92	0.95
Measured heat transfer coefficient considering the heat flux in the middle of the module Ug,wmf Tolerance ΔUg,wmf	**[W/ m^{2}K] [W/ m^{2}K]**	**1.1 ± 0.15**	1.05 ± 0.15

3. **CONCLUSIONS**

As far as the electrical performance of the modules is concerned, it has been observed that temperatures and module inclination have influenced the amount of energy produced by the modules as well as their performance. Together with the type of integration and the orientation they are the main parameters that influenced the module performance.

In particular the module integrated at 30° (BIPVTP/21) had a highest energy production in comparison to the one integrated at 90° (BIPVTP/22). As expected the other parameter that influenced the performance was the working temperature of the modules. High temperatures during the spring and summer months resulted in a decrease of performance for both modules (especially for c_Si modules).

The higher working temperatures of the module integrated at 30° (BIPVTP/1) had a significant annealing effect on it which, consequently resulted in a better performance, followed by the module integrated at 90° (BIPVTP/2) and ultimately, the ventilated module at 90° (BIPVTP/3) demonstrated the lowest performance of these three, as well as the lowest working temperature throughout the whole monitoring period.

The high temperatures reached have influenced greatly the performance ratio of the modules. In particular the higher working temperatures of the module integrated at 90° (BIPVTP/20) had a great annealing effect on it, which consequently resulted in a better performance. Then followed by the module integrated at 30° (BIPVTP/19) and ultimately, the ventilated module at 90° (BIPVTP/18) demonstrated the lowest performance of these three, as well as the lowest working temperature throughout the whole monitoring period.

For the flexible a-Si modules on the roof, it has been observed that the different temperatures reached for each module had a small influence on the performance of the modules, mostly because these differences were not too big. The modules on zinc and aluminum sheets demonstrated lower temperatures and that is because of their mounting solution which was not integrated on the roof like the rest. There were no influences of the inclination since all modules were at 0°.

For the thermal part, the BIPVTP/21 module demonstrated satisfactory U and g values due to the technologies used. Its U-value and g-value were measured to be about 1.1W/m2K and 0.153 respectively. The same results were obtained also for the BIPVTP/1 with values of U and g of .05W/m2K and 0.120 respectively. A low g-value has also an impact on the visual transmission of the window.

In conclusion, it could be said that the performance of BiPV modules is influenced by the combination of the:

1. type of integration,
2. inclination,
3. temperature coefficients of the modules and
4. annealing effects.

The thermal characteristics of the modules exhibited satisfactory values respecting those of the Minergie® standard and strictly depend on the optical property of the glass and of the gasses. The working temperature of the photovoltaic part seems to have a small influence on the total solar heat gains. Further investigation have to be done in this sense in order to assess in advance the thermal characteristics of the BiPV windows (U-value and g-value).

However, in addition to the aspects above, also the lifetime and long-term degradation of the modules, the aesthetics and cost must be taken into consideration, in order to let the architected consider PV technologies as possibility for building envelope.

Further investigation could be done concerning the impact of BiPV module (especially semi-transparent modules) on the indoor comfort and on the thermal behavior of the room. In particular further study can be done on the daylighting influence of semi-transparent BipV modules and the possibility of using PV module as glare control system. Really few studies exist about the influence of integrating PV module on human behavior and comfort, with consideration also on heating and cooling demands).

4. REFERENCES

[1] S.Dittmann et al., Energy Yield Measurements at SUPSI - Importance of Data Quality Control and its Influence on kWh/Wp Inter-Comparison, 26th EPVSEC, Hamburg (D), September 2011.

[2] G. Friesen & S. Dittmann, et al.: Performance Intercomparison of 13 Different PV Models Based on Indoor and Outdoor Tests, 25th EPVSEC, Valencia (ES), September 2010.

[3] H. Simmler, B. Binder, Experimental and numerical determination of the total solar energy transmittance of glazing with venetian blind shading, Building and Environment, Volume 43, Issue 2, February 2008, Pages 197-204.

[4] P. G. Loutzenhiser et al., Empirical validations of solar gain models for a glazing unit with exterior and interior blind assemblies, Energy and Buildings, Volume 40, 2008, Pages 330-340.

[5] A. Chatzipanagi et al., Evaluation of 1 year of monitoring results of a testing stand for Building Integrated PV elements, 26th EUPVSEC, 5CO.12.3, Hamburg 2011.

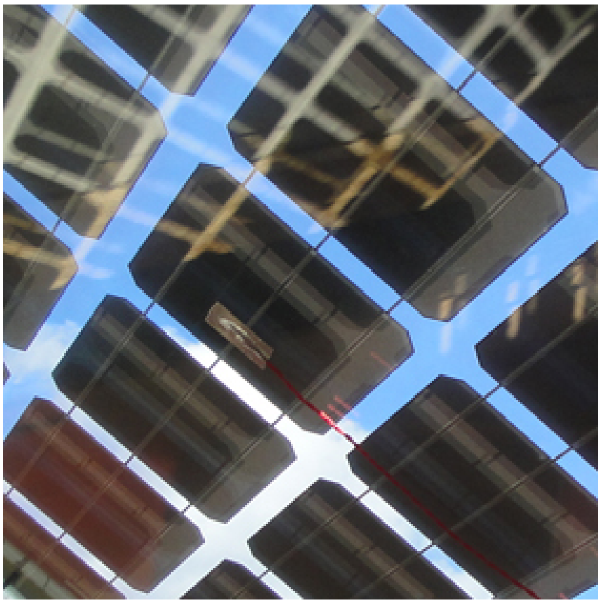
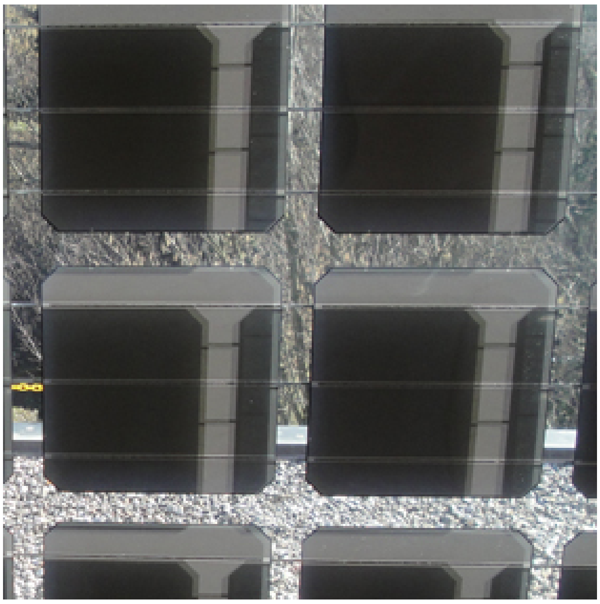
[6] K. Nagel et al., Low energy house for testing building-integrated PV elements, 25th EUPVSEC, 5BV.5.6, Valencia 2010.

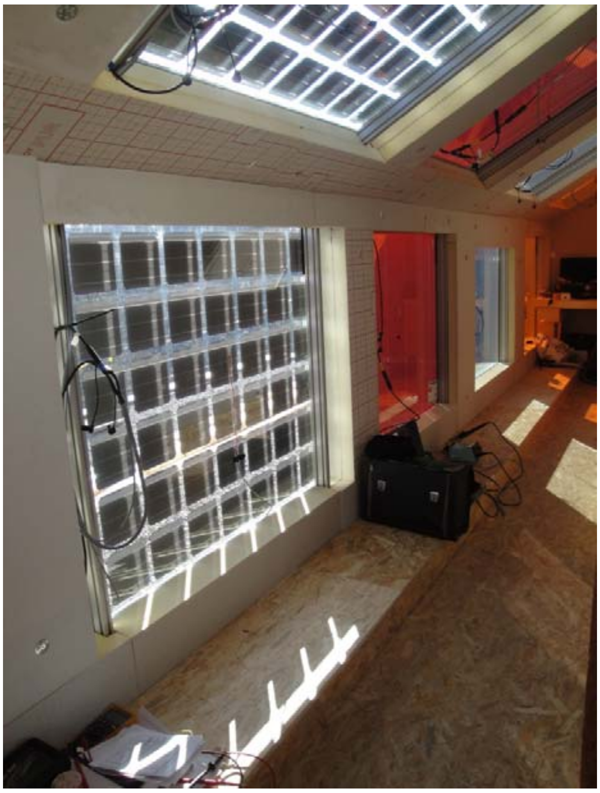
5. ANNEXES

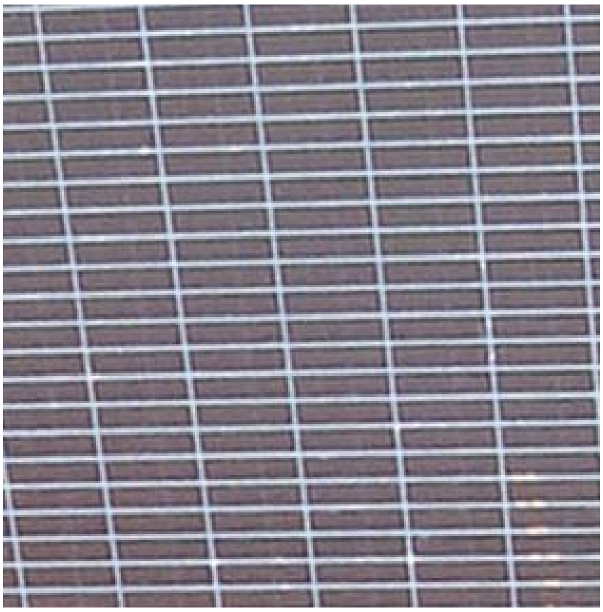
5.1. Photographs of modules and testing stand

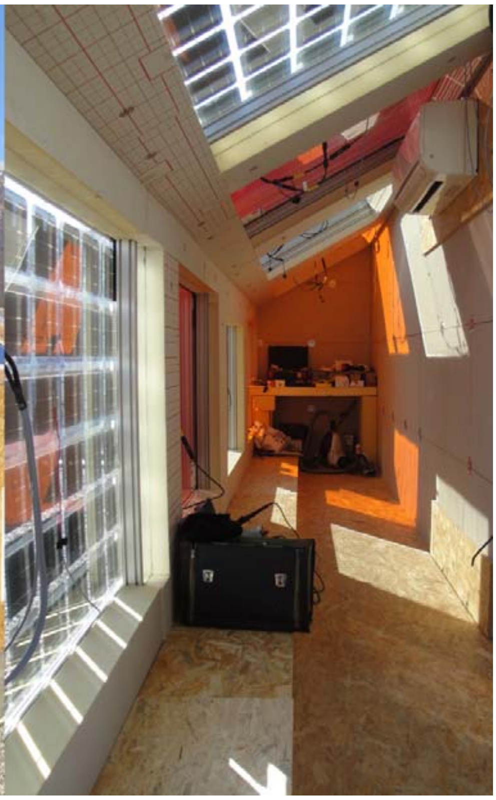


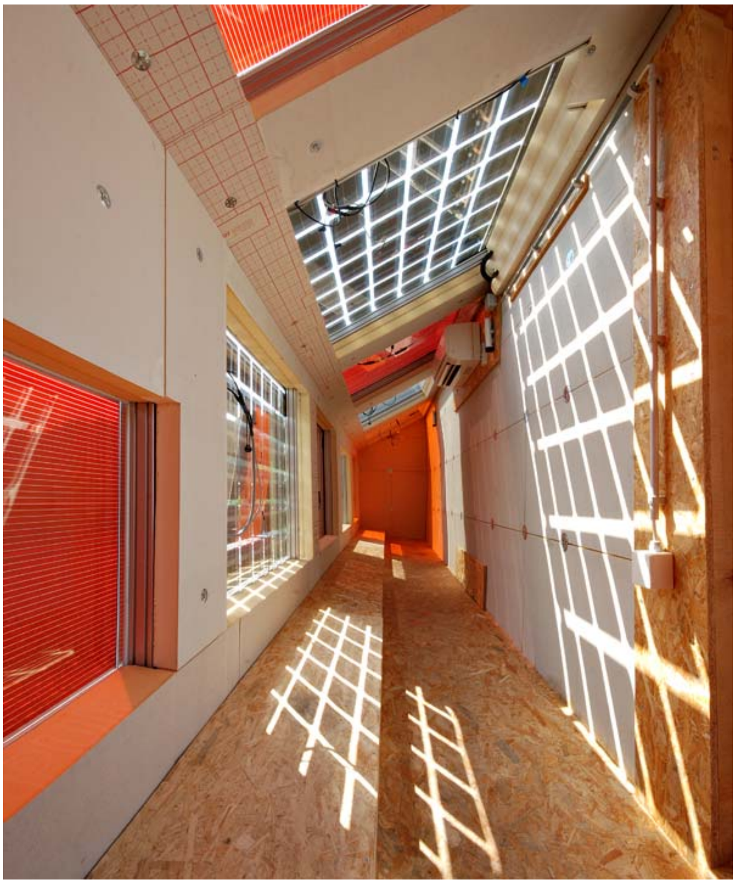










5.2. Determination of “Day Types” – Classification of days

The days are grouped in three different classes: clear; cloudy and overcast.

First the sky ratio Sr and the Perez’s clearness index ε are used to group all days in three classes (clear, cloudy, very cloudy). The ranges of both criteria are:

$Sr < 0.24$	$4.50 \le \varepsilon$	clear
$0.24 \le Sr < 0.80$	$1.23 < \varepsilon < 4.5$	cloudy
$0.80 \le Sr$	$\varepsilon \le 1.23$	overcast

In the case that days are not clearly matched to a group, a third criteria, the clearness index kt , is added.

$0.45 \le kt$	clear
$0.25 < kt < 0.45$	cloudy
$kt \le 0.25$	overcast

Calculations:

1. Perez’s clearness index ε:

$$\varepsilon = \frac{\frac{\sum \mathrm{Gdiff} + \sum \mathrm{Ees}}{\sum \mathrm{Gdiff}} + 1.041 * \gamma_z^3}{1 + 1.041 * \gamma_z^3}$$

$$\mathrm{Ees} = \frac{\mathrm{Edir,o}}{\cos(\gamma_z)}$$

Ees - beam normal radiation

γz - zenith angle [rad]

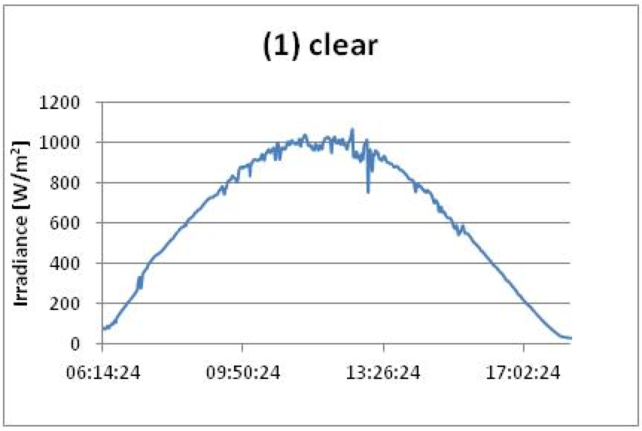
1. Sky ratio Sr:

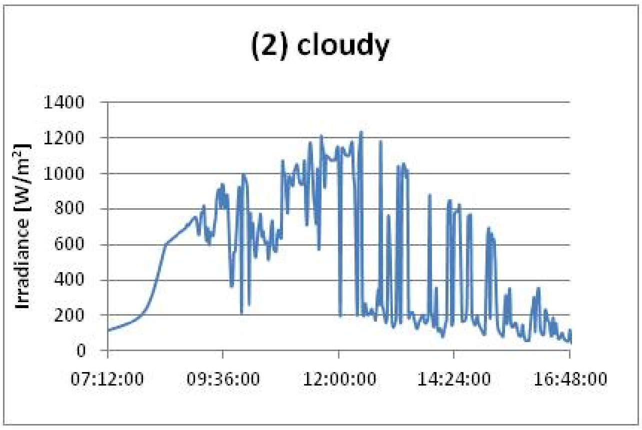
$$Sr = \frac{Gdiff, o}{Gglob, o}$$

2. Clearness index kt:

$$kt = \frac{Gglob, o}{Gex, o}$$

3. Gex,o - extraterrestrial irradiance (horizontal)





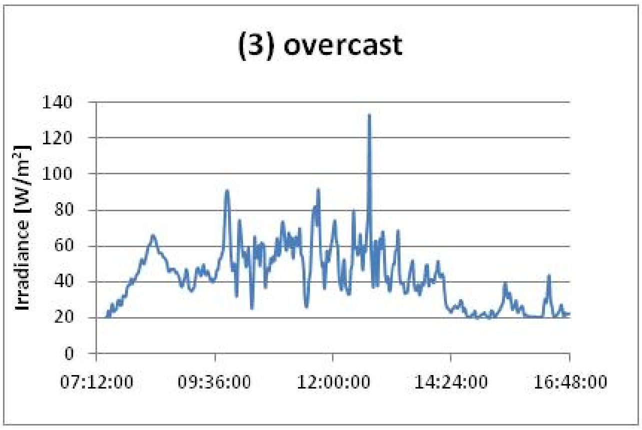


Figure 9: Example of day types: (1) clear, (2) cloudy, (3) overcast.