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Solar radiation measurement on thin-film cylindrical photovoltaic surfaces

LORENZO MARCOLINI*

Abstract. The measurement of the intensity of solar radiation is one of the environmental measurements required to test performance (efficiency) in a photovoltaic (PV) system. The procedure is part of the administrative protocol for eligibility for Italian state incentives, granted by GSE (Gestore Servizi Elettrici); it is also recommended to the system designer as an addition to the declaration of compliance. In PV systems with flat-plate PV modules this measurement is automatically calculated. Once the system rated power is manually entered and the environmental measurements are acquired by probes and sensors, the unit processing station calculates if the conversion of solar radiation power into electrical power (DC side) and that of direct current into alternating current (AC side) are greater than the minimum performance values defined by CEI (Comitato Elettrotecnico Italiano). Conversely, radiation intensity on PV cylinders cannot be measured following the guidelines of IEC 61646 (transposed into Italian legislation as CEI 82-25) which are specifically written for flat modules, although datasheets by Solyndra, manufacturer of cylindrical modules, certify their rated power with reference to this standard. The present study outlines the method used to measure the components of direct, reflected and diffuse light radiation on the surface of a cylindrical PV module and justifies the hypothesis, experimentally tested, that IEC standards are met when reducing global radiation intensity by a certain percentage. These tests have been carried out in cooperation with Hessiana srl, who have installed a cylindrical PV system on the roof of an industrial building in central Friuli.

Key-words. solar radiation intensity, performance (efficiency), rated power, PV flat modules, PV cylinders.

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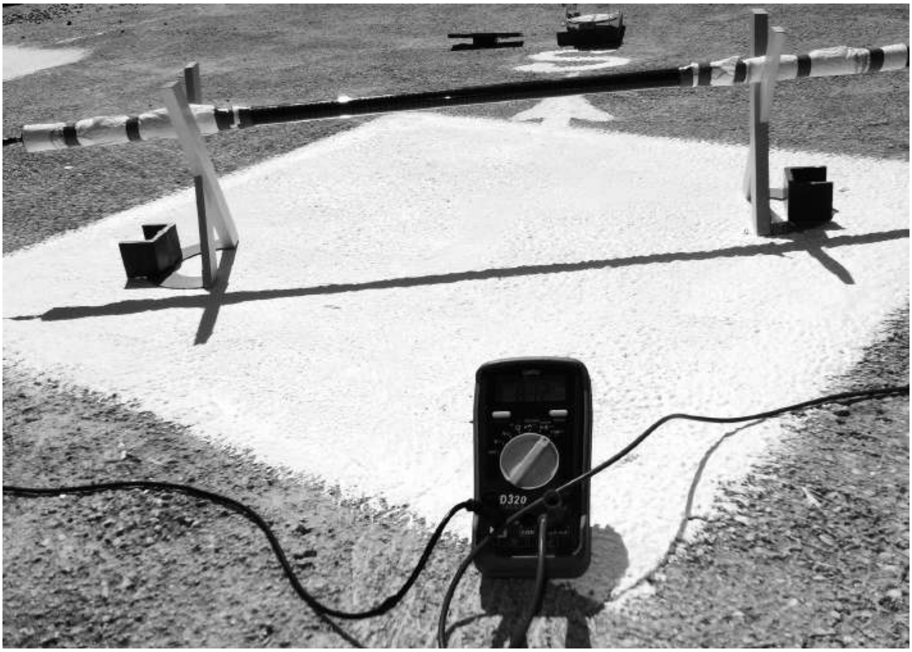


Figure 1.

1. Introduction. Almost all PV modules, whether crystalline silicon or thin film, leave the production chain as flat-plate modules. The exception is the CIGS thin-film cylindrical module manufactured by Solyndra (Fremont, California), a special technology that covers a small niche of the market, now put on ice as a result of the bankruptcy process of the Californian company (Figure 1 shows a PV cylinder in an outdoor laboratory)[1].

Nowadays, there are hundreds of brands of flat modules on the market. The governments of the developed countries have appointed special commissions of experts to write norms promoting the trade of goods, protecting the environment, and ensuring the safety of workers and users; they are also responsible for laying out the guidelines on the testing procedures required for product certification. In the field of electrotechnics, these norms are known by the acronym CEI EN/IEC (CEI stands for Comitato Elettrotecnico Italiano, EN refers to CELENEC, the European Committee for Electrotechnical Standardisation, and IEC stands for International Electrotechnical Commission). In particular, guideline CEI 82-25 indicates the procedure to follow for testing the functionality and minimum performance of a PV plant.

These operations are generally

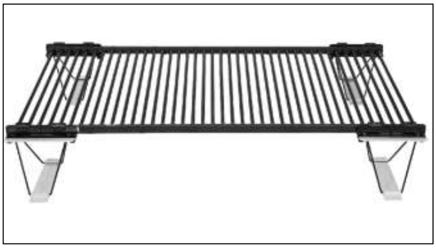
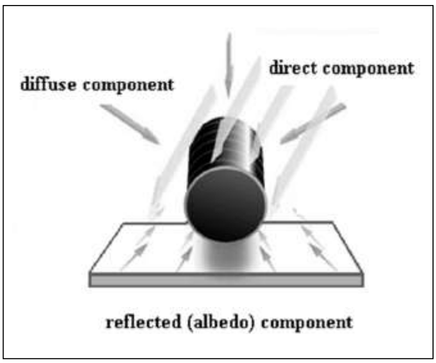


Figure 2.



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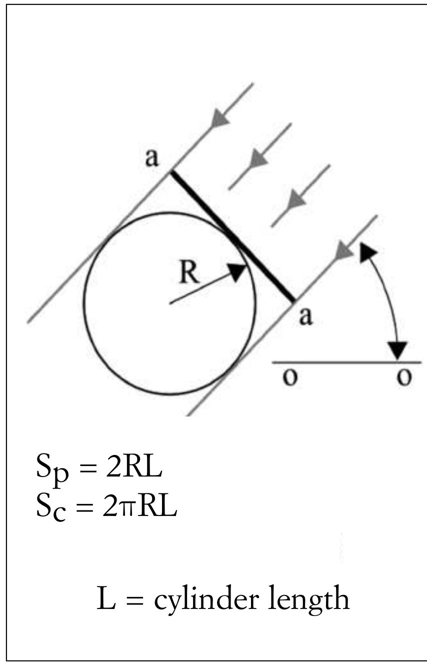


Figure 4.

known as "functional and technical checks". Performance or efficiency, sometimes improperly called yield[2], is calculated by entering in specific formulas the rated power declared by the manufacturer and the environmental and electrical quantities measured. The measurement operations, in particular solar radiation and temperature, require the use of a solar meter and a temperature sensor, the first one positioned directly on the module and the second one attached to its back.

The standard procedure of radiation measurement only considers flat surfaces and is not applicable to cylindrical modules, because cylinders not only receive direct radiation but also the radiation reflected by the roofing material (called albedo component). In Figure 2 we see cylinders arranged in a panel and positioned at a certain height above the rooftop, and in Figure 3 a cylinder invested by direct (rays with parallel directions), diffuse (rays with random directions) and reflected sunlight.

In its certifications list, however, the Solyndra datasheet also includes IEC 61646 (implemented in Italy with the addition of the acronym CEI/EN), a performance standard obtained by placing a crystalline or thin-film flat module in the darkroom of a solar simulator, in front of a series of solar light lamps.

If we follow the guidelines of IEC

61646 and apply the formulas of CEI 82-25 to a cylindrical module, we cannot obtain a positive test result, because the solar meter only measures the sunlight falling directly on the tangent plane *a – a* (in the case of Figure 4 the plane is perpendicular to the rays) and not the total amount of radiation distributed over the entire lateral surface of the cylinder, not to mention the fact that rays impact in a different way on a semi-cylindrical and on a flat surface.

For all the considerations that will be developed later, we need to provide some basic information on physics, technology and plant data.

The light propagation model employed for the purpose of this work is based on the postulates of geometrical optics. According to this model, each point of a plane wave with a constant phase emits a wavelet that may be replaced by a straight line outgoing from the point, the so-called rays. Considering the sun a source at infinite distance, rays can be considered parallel and uniformly distributed in space.

The study of the propagation of light in gases and its incidence on surfaces also takes into account other phenomena such as diffusion, reflection, refraction and diffraction. All these can be effectively described by the ray model and the first three will be examined in the following paragraphs. Conversely, the diffraction phenomenon, that is the apparent bending of waves around small obstacles, can be neglected, which in simple terms means considering light and shadow as clearly divided, which is indeed what our eye usually perceives.

The technology of Solyndra cylindrical modules derives from fluorescent tubes and each cylinder is made up of two tubes one inside the other. A layer has been developed on the outside part of the inner tube that includes up to 200 PV CIGS cells rolled up on the entire cylindrical surface[3]. Moreover an overlapping special "optical coupling agent", deposited on the CIGS layer, concentrates the sunlight that shines through the outer tube. After inserting the inner tube in the outer tube, each cylinder is sealed with glass and metal to avoid penetration of moisture, which would decrease the performance of PV CIGS film, and fastened to a rack. Each panel contains 40 cylinders positioned at a height of about half a metre from the floor.

The main technical datum for a panel is the so-named peak power or rated power[4]. In the case of the Hessiana PV system, it is calculated by simply adding the individual power ratings of each panel, as written in the datasheets released by the manufacturer: N_m = 576 panels with a unit rated power of P_n = 200 W gives a total PV field rated power of $P_{n,pv}$ = 115.2 kW.

In the following paragraphs a ratio between the amount of global solar radiation falling on a flat module and the same amount falling on a cylinder surface will be estimated, then a theoretical justification of the estimated value will be given and finally we will discuss the experimental data extracted from laboratory and PV plant testing.

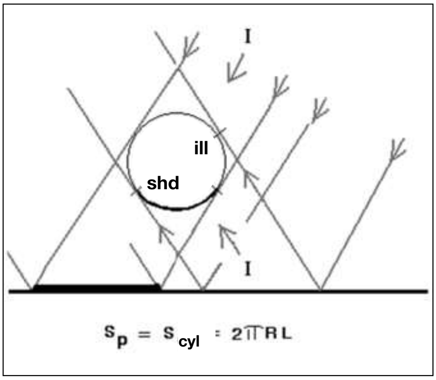


Figure 5.

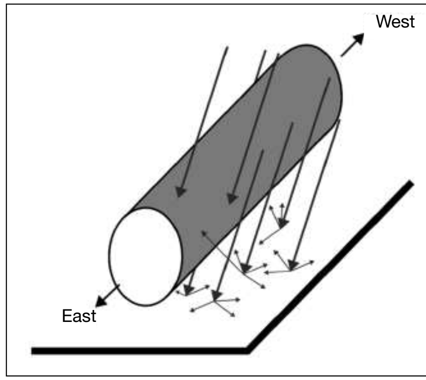


Figure 6.

2. Measurement of solar radiation on flat and cylindrical surfaces. Some methodological considerations. A sunny PV surface is generally irradiated by direct, diffused and reflected solar radiation. Direct radiation is composed of sun rays, diffused radiation comes from the sky (and clouds), and reflected radiation is caused by light-reflecting elements such as water, plants, buildings, etc. In the subsequent considerations we will ignore the reflection and absorption of light by the panel protection glass.

The cylinders have been oriented in an east-west direction and arranged in such a way that they are parallel to the surface of the rooftop, so as to obtain a uniform illuminance distribution along the semi-cylinder throughout the day, with the rays hitting the cylinder at the same angle on every east-west direction parallel to the central axis[5].

If we only consider direct and diffuse radiation, a flat PV module evidently ensures greater conversion efficiency than a cylindrical module of the same surface area and manufactured with the same photosensitive material. And in fact, the semi-cylinder in shade is hit by an amount of light, reflected from the roof, lower than the amount of sunlight which would fall on a flat module of the same surface area, fully exposed to the sun. This intuition is borne out by the analysis of a single cylinder: the direct component of intensity I hitting the semi-cylinder, partially shadowed (shd) and partially illuminated (ill), and reflected by the rooftop, overlaps and is added to the direct component of the same intensity hitting the semi-cylinder in full sun only in the ideal case of a perfectly specular reflective surface (Figure 5).

In a real-life situation, part of the radiation is absorbed by the roof and part is scattered in all directions (see Figure 6), and effectively a roof is not a mirror-like surface like a lake on a sunny day, reflecting all direct and diffused light so that the landscape around the lake is exactly mirrored

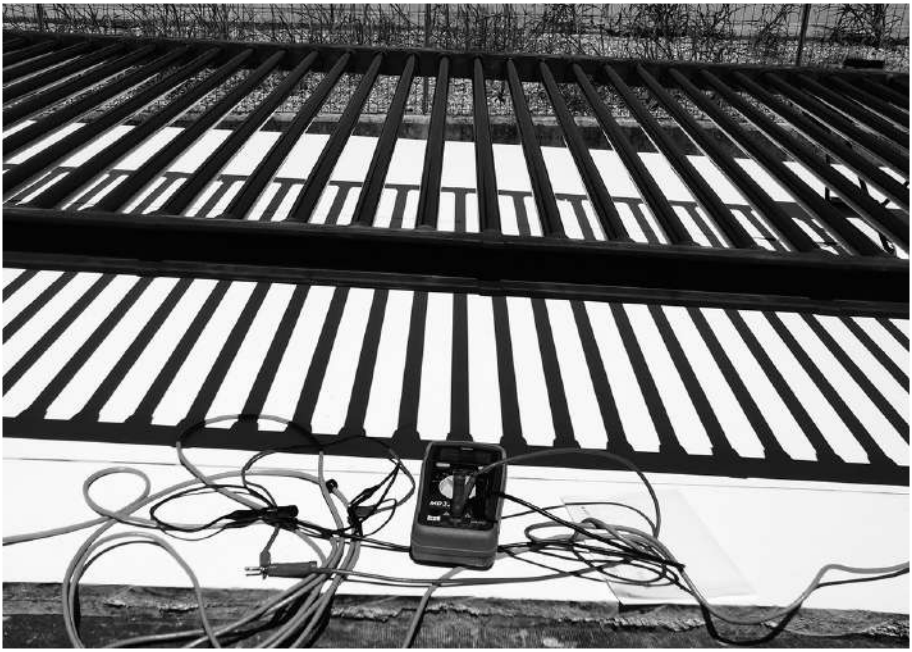


Figure 7.

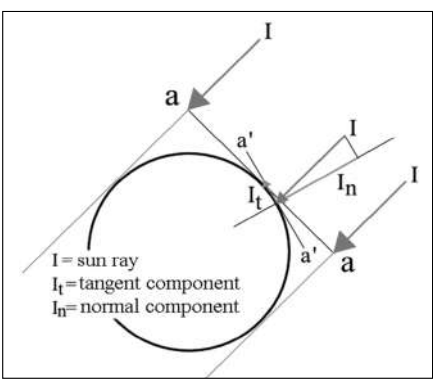


Figure 8.

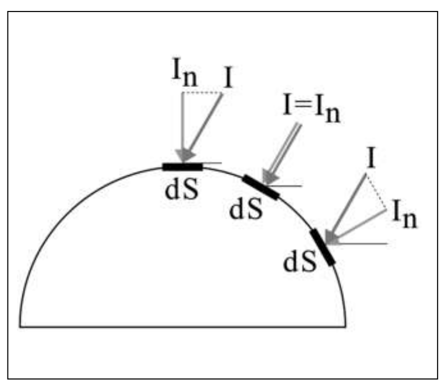


Figure 9.

on the water surface. In addition, the cylinder is not isolated, and the other cylinders lined beside it reflect their shadows on the rooftop, reducing the net reflective surface (in Figure 7 cylinders in a laboratory situation under the sun).

Let us now do some quantitative reasoning on efficiency, measurement, considering a PV semi-cylinder in full sunlight and placing a solar meter on the tangential plane *a – a* (see Figure 8). The first observation is immediate: the semi-cylindrical surface below the plane *a – a* in a cylinder of radius R is larger than the plane surface that is above it, and therefore the power density measured on the tangential plane surface is greater than the one measured on the cylindrical surface[6].

A first evaluation of the percentage reduction in power density between the tangential plane *a – a* and the semi-cylindrical surface could be given by the ratio between the two surfaces $(S_c/2)/S_p = \pi/2$. Yet we cannot consider this result a proportionality factor to be applied to the relationship between the two power densities, because the reduction of power density refers to the solar radiation perpendicular to the planes *a – a* and *a' – a'*. And in fact, the quantity $(S_c/2)/S_p$ is not equal to the ratio between direct radiation densities $(I/S_p)/(I_n/(S_c/2))$, because I/I_n is not unitary but $I \geq I_n$ (with reference to every elementary surface dS, the tangential radiation I_t at the plane *a' – a'* slips away by a quantity which depends on the inclination of the sun ray) (see Figure 9). A calculation to take into account the variation of I over I_n will be described in the next paragraph.

At this point let us formulate the hypothesis that the part of the semi-cylinder in shade, lying on the opposite side to the semi-cylinder facing the sun, does not receive any of the three components: reflected, direct and diffuse; consequently the percentage reduction in density radiation from the surface of the tangent plane (S_p) to the cylinder surface (S_c) is calculated with the formula:

$$\Delta J\% = [I/S_p - I_n/(S_c/2)]/(I/S_p) \cdot 100 \tag{1}$$

If we ignore the loss of the tangent component in all points of the cylinder surface $(I = I_n)$ the calculation leads to a percentage reduction of approximately 36.3%.

Instead, if we consider a single ideal cylinder of unlimited radius, so that the cylinder surface coincides with the plane surface (with a limit value of $S_p = S_c/2$ and consequently $I = I_n$), then we do not have any reduction in radiation density, that is 0% of percentage decrease.

Having calculated the two limit values we can draw the following conclusion: the percentage decrease of direct radiation from the plane *a – a* to the semi-cylinder below it, measured by a solar meter placed on the plane, under the hypothesis to neglect the reduction in direct radiation from the plane *a – a* to the semi-cylinder due to a loss of the tangential component, does not exceed 36.3% approximately, so the percentage intensity value is inside the following range:

$$0 < \Delta J\% < 36.3\% \tag{2}$$

Later in this paper we will adjust the upper limit of (2) by taking into account the decrease of direct radiation from the tangential plane to the semi-cylinder, the influence of diffuse

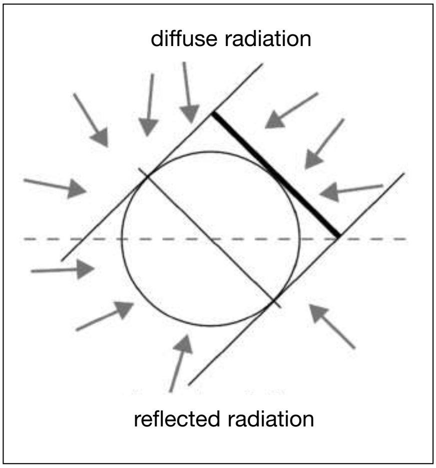


Figure 10.

light and, last but absolutely not least, the impact of the albedo component on the semi-cylinder in shade.

Before we continue, a short digression is in order. When a PV surface is exposed outdoors on a beautiful sunny day, both diffuse and direct radiation affect PV production, while a PV module in a laboratory situation is only illuminated by direct light. Let us consider, then, the characteristics and effect of diffuse radiation on PV efficiency[7]. Diffuse solar radiation comes from the sky and is partially reflected by the roofing material (see Figure 10).

Diffuse radiation can be compared to the disordered movement of the electric charge in conductors or semi-conductors: as electric carriers in the absence of an electric field move in a random direction inside matter, so do the photons of diffuse light in the atmosphere. If we can explain the regular movement of particles with elegant equations – and in fact, we will later use geometrical methods to study the propagation of direct sunlight in the air – we must rely on statistical data for the calculation of parameters involving the random movement of enormous populations of particles.

Firstly, we need to establish in what percentage diffuse radiation is investing the two semi-circumferences lying above and below the tangent plane *a – a*. Let us hypothesise the ideal case of an isolated cylinder, so as to avoid the influence of shadows on reflected light. Also, let us consider the ideal situation of a perfectly clear and cloudless sky, the weather everyone would wish for when testing PV systems.

To begin with, we restrict our analysis to the *semi-cylindrical surface facing the sun*, and investigate if there are significant differences in the intensity of scattered light when we compare a semi-cylindrical and a plane surface of equivalent extension.

Figure 11 shows a particular case where a perpendicular component of a radiation of intensity I generally inclined on the plane *a – a* decreases its amplitude passing from the plane *a – a* to the tangent plane *a' – a'*. If we consider the relationship along the semi-circumference of the cylinder illuminated by the sun between the two components $I_{n,p}$ relative to the plane *a – a* and $I_{n,c}$ along the same direction relative to the other plane *a' – a'*, we observe with $\alpha < 90°$ the relationship $I_{t,p} > I_{t,c}$ ($I_{n,p} < I_{n,c}$) and the opposite result if $\alpha > 90°$, that is $I_{t,p} < I_{t,c}$ ($I_{n,p} > I_{n,c}$). The theorem in the note[8]

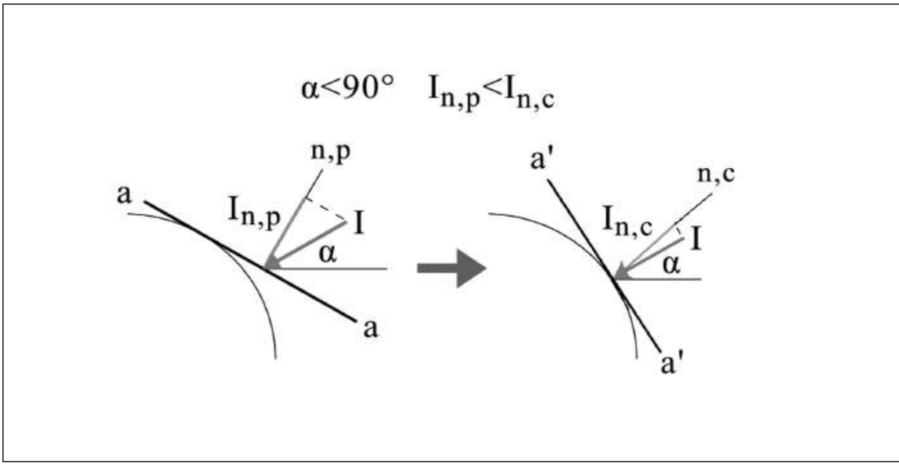


Figure 11.

makes us think that during the day the effects compensate each other, and the normal diffuse component referring to the plane *a – a* and the semi-cylinder *a' – a'* illuminated by the sun would be basically the same: $D_{ill} \cong D_p = D_c$.

In cloudy conditions photons strike the two surfaces from all directions and there is no reason they give priority to the flat surface rather than the cylindrical one, so the above conclusion is confirmed.

Let us consider at this point the *semi-cylinder projecting its shadow* on the rooftop (see Figure 1 above). The scattered light which does not fall on the upper section of the cylinder ends up on the building roof. This albedo component D_{alb} cannot be greater than the diffuse radiation that would fall on the cylinder surface if it were exposed to the sun – in that case the roof surface would produce an effect of light concentration, which is not possible. If we also add the consideration that the roof surface absorbs part of the radiation and is not specular, we can conclude that *the total diffuse radiation will approach at most the density value that would be measured on the plane surface equivalent in extension to the lateral surface of the cylinder*:

$$D < D_{ill} + D_{alb} \qquad (3)$$

To reduce the difference $\Delta D = D - (D_{ill} + D_{alb})$ the installer recommends that the roof surface under the panels be painted white. A white roof surface, according to estimates by the panels' manufacturer Solyndra, would recover up to 15% ± 20% of global radiation compared to a black one[9].

We have considered, up to this point, the intensity of light distributed around the cylinder. Let us now study *the path of light inside the cylinder*. It has already been said that the

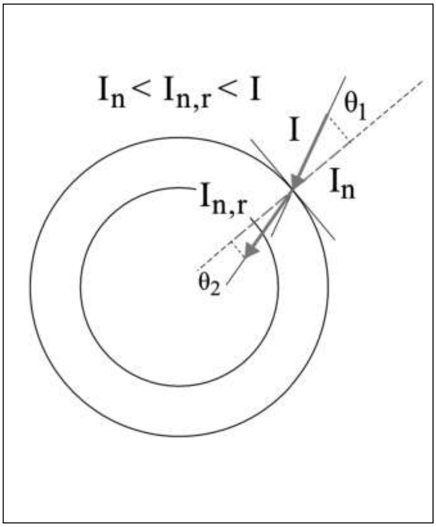


Figure 12.

Solyndra cylinder is composed of two tubes, the outer made of glass and the inner composed of two films: an optical concentrator film over a photosensitive CIGS film. A sun ray, before reaching the optical concentrator, undergoes a partial concentration of light due to refraction, the particular phenomenon of 'straightening' that happens when a solar ray passes from one medium to another of different density, in our case from air to the glass of the outer tube. This rectification effect adds up to the optical concentrator effect at any time during the day. Concentration, therefore, increases the performance of a PV cell (the same power is concentrated onto a smaller surface) as a greater perpendicular value of the direct component passes from air to glass and consequently there is a reduced loss of the tangent component ($I_{n,r} > I_n$ as in Figure 12).

In this aspect the PV cylinder acts as a passive solar tracker, but its performance is much lower than that of a dynamic tracker.

The statement by Solyndra that one advantage of its cylindrical modules is their ability to track the sun's radiation without the need for moving parts as in traditional solar trackers (which continuously maintain the relation of equality $I = I_n$) is partially true only with the sun in a position close to solar noon, while with sun rays increasingly inclined from east to west, the intensity I is increasingly distant from I_n.

Yet compared to equivalent systems with flat modules without concentrators, solar concentration increases both production and performance. Cylindrical modules, in fact, present a flatter potency curve compared to flat modules without concentration which show a peak; consequently the variation of density $\Delta J\%$ in (2) is shifted more towards zero.

Let us evaluate this increase in performance only with reference to the effect of refraction.

The refraction angle θ_2 obtained from Snell's law depends on the angle of incidence θ_1: sen θ_1/sen $\theta_2 = n_{12}$ with air/glass coefficient $n_{12} = 1.55$. In any case, the calculation of the percentage variation of the normal component I_n for any inclined angle α on the plane of the horizon at the latitude of Talmassons (where the plant is located) between the two solstices ($21° < \alpha < 67°$) and along the circumference, is a few percentage points. In practice the variation $\Delta J\%$, compared to the situation envisaged without refraction and concentration, moves toward the lower limit but will never be zero. The integral calculus for any given value of $J = f(\alpha)$ is:

$$\Delta J = J - \iint \cos(\arcsin[1/n_{12}\text{sen}(\theta_1(\alpha))])d\alpha \quad (4)$$

The $\Delta J\%$ variation differs from zero but is closer to zero compared with systems without concentration.

We can conclude, intuitively but also validated in this by geometrical optics, with this general statement: *the density of global radiation investing a lateral surface of a cylinder lying in an east-west direction (but also in any other direction) is lower than the global radiation intercepted by a plane surface of equal area in all possible weather conditions.*

Now our aim is to determine the reduction percentage with more precision.

3. CEI testing conditions. CEI 82-25 standards require that PV systems have a minimum efficiency level of 75% with at least 600 Wm^{-2} of sunlight intensity. The overall efficiency of a PV system expresses how much light power is transformed into electric power. Calculated upstream the inverter, converting the direct current (dc) output of the PV plant into alternating current (ac), efficiency evaluates the plant's nominal power against light power.

Since a PV plant is a linear physical system, its efficiency can be calculated on the basis of the power of a single Solyndra cylinder viewed as a solar battery with positive and negative signs at each end (Figure 13).

Figure 13.

In its technical datasheet, the modules' manufacturer Solyndra certifies a rated power of $P_n = 200$ W for each module. The calculation of a module's efficiency is given by the formula

$$\varepsilon\% = [(P_n/(N \cdot S_c)]/G_{STC} \cdot 100 \quad (5)$$

where N = 40 is the number of cylinders in the module; $G_{STC} = 1000\ Wm^{-2}$ is the radiation intensity value under Standard Test Conditions (STC) measured on the plane; $S_{cyl} = 3.14 \cdot 2R \cdot L$ (2R = 2.2 cm; L = 100 cm) is the cylinder's surface. The calculation leads to an efficiency value of $\varepsilon\ \% = 7.24\%$, which is much lower than the STC efficiency of any thin-film module.

The manufacturer has not provided data on the laboratory efficiency of a CIGS cell or a module, but technical literature indicates at least 13% efficiency and beyond[10]. Using this data we obtain an efficiency variation of approximately 44.3%, a value outside the range displayed by (2), with a deviation from the value previously found of $\Delta = 44.3\% - 36.3\% = 18\%$. Considering that (2) does not take into account the loss of global radiation by the semi-cylinder in shade, we have reason to adjust (2) to the new range:

$$0 < \Delta J\% < 44.4\% \qquad (6)$$

If this hypothetical efficiency value is subtracted from the upper limit given by (6) and equated to the value of 7.24%, the result will be about 12% which is very close to the figure declared by the manufacturers of thin film.

In non-STC, G_{STC} is replaced by G: $0.6 \cdot G_{STC} < G \leq G_{STC}$ and then (5) can be written as:

$$\varepsilon\% = [P_n/(N \cdot S_c)]/G \cdot 100 \qquad (7)$$

where P is the transformed electric power.

Following the reasoning of the previous paragraph, the radiation measured on a cylindrical surface developed on a plane is, in actual fact, higher than the radiation intensity falling on the cylindrical surface; so in order to calculate the effective efficiency value of a PV cylinder, we need to correlate the global intensity of the solar radiation falling on a cylinder surface with the real power being measured. But while real power can be easily measured with conventional testing equipment, a solar meter cannot calculate the global radiation falling on the entire cylinder surface under STC, as required by the CEI guidelines which are written for flat modules.

We can understand why we cannot match the required minimum efficiency value (CEI 82-25 calls it "yield") if we consider the following formulas as laid out in the CEI guidelines, which are used by the software of the processing unit:

$$\begin{aligned} &P_{dc} > 0.85\, P_n \cdot G_p/G_{STC} \\ &P_{ac} > 0.9\, P_{dc} \end{aligned} \qquad (8)$$

where:

– P_{dc} is the output power of the PV generator measured in kW with an accuracy higher than 2%;

– P_{ac} is the active output power of the inverter measured in kW with an accuracy higher than 2%;

– P_n is the rated power of the PV generator measured in kW, calculated by summing the rated power of each module as published in the manufacturer's datasheet;

– G_p is the radiation intensity measured in Wm^{-2} calculated on the modules' plane: a PV cell solar meter with an accuracy higher than 3%, a thermoelectric solar meter with an accuracy higher than 1%;

– G_{STC} (I_{STC}) is the solar radiation under STC measured in Wm^{-2}.

According to the interpretation of CEI 82-25, the first formula of the (8) above checks the value of yield of η_{dc} on the dc side and the second checks the η_{ac} on the ac side; moreover the formula clearly indicates that if the product of the factors $P_n G_p$ is higher than the real yield being measured then the verification fails. To verify the inequality it is necessary to decrease the product.

The first factor cannot be changed because it has been declared by the manufacturer, so we must decrease G, subtracting from the global intensity measured on the module's plane the sum of the percentages that do not enter the cylinder.

In the following paragraphs we will present theoretical and experimental considerations on how to estimate the real radiation intercepted by the cylinders as a whole.

4. Theoretical method for a calculation of the distribution of global radiation in flat and cylindrical surfaces. The yield of a PV plant depends on the intensity of solar radiation falling on a PV surface in a certain period, so the performance of a PV module depends on the particular hour of the day, day of the year and on weather conditions. All the following considerations are based on environmental conditions close to STC, that is blue cloudless sky and negligible relative humidity, a pleasantly cool temperature and no wind. These weather conditions are very rare and when they happen we say, "Earth is the garden of Eden!". For this reason testing is mostly carried out on paper, except in cases of necessity when the owner complains that the energy production of the PV roof is distant form that predicted by the installation company.

We will now devise an analytical procedure for the calculation of the most plausible value within the range of uncertainty written in (6).

We have already classified the three components of global solar radiation – direct, diffuse and albedo (reflected):

$$G = I + D + R \qquad (9)$$

where G is the global radiation measured at ground level.

Let us first consider the solar radiation falling on the *semi-cylinder facing the sun.* The calculations and considerations rely on the following assumptions:

a) the value of direct radiation I_n that enters normally to the surface of the cylinder is calculated by an analytical procedure using a spreadsheet;

b) the albedo reflected on the cylinder surface facing the sun is neglected;

c) direct radiation I_n maintains a constant value along the axis of the cylinder excluding the edges, where we find a negligible variation of a few percentage points (see Figure 14).

Before we move forward, let us consider a few interesting points.

Direct radiation does not uniformly irradiate the PV surface along the entire circumference, so the intensity vector I_n must be referred to an elementary surface, as small as possible to be measured and as small as we want in calculation, to get close to the real value before proceeding with an integration.

The I_n component along the semicircumference varies from zero at the end of the diameter (the point of tangency of the solar radius with the cir-

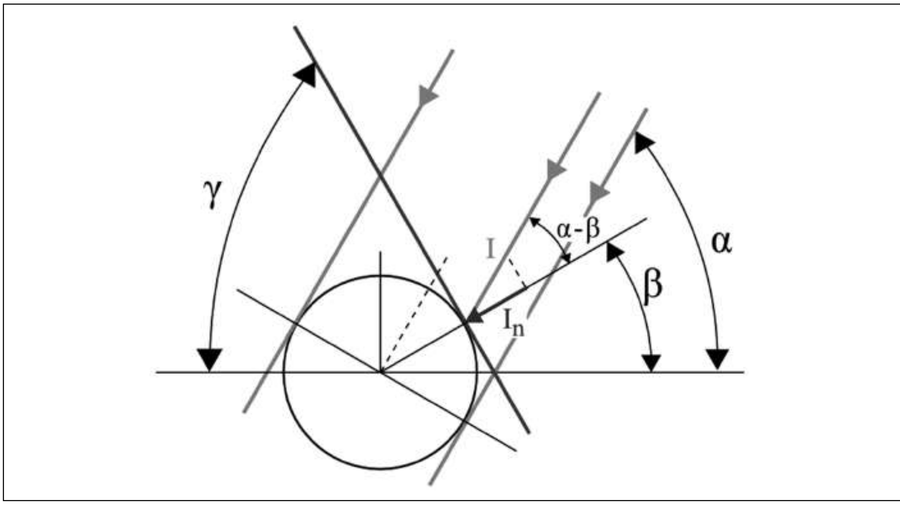


Figure 14.

cumference) to a maximum value when the direction of the vector I is the same as I_n ($I = I_n$).

The formulas for the calculation of the normal component of power intensity distributed on the surface of a PV semi-cylinder facing the sun are written in a note[11].

For all inclinations of the sun rays, the simulation produces a percentage decrease in intensity of $\Delta I\% = 36\%$, pretty much the same result obtained by calculating the density variation $\Delta J\%$ in (1).

The hypothesis formulated in b) means that the roof does not have reflection (R = 0) and (9) becomes:

$$G = I + D \tag{10}$$

The measurement of the amount of radiation intensity from which the percentage reduction is subtracted is obtained by placing a solar meter on a tangent plane with a tilt angle[12] calculated as $\gamma = 90 - \alpha$, that is a typical setting when a solar meter is oriented against the sun.

The formula for the calculation of global solar radiation on the plane of the semi-cylinder facing the sun is as follows:

$$G_{ill} = k_S (I + D) = k_S [k_{red} (G - D) + D] \cong 0.23\, G = 23\%\, G \tag{11}$$

where:
$D = k_{dif} (1+\cos\gamma)/2)\, G$, $k_{dif} = 0.2$ diffusion coefficient (see note[7]);
$k_{red} = 0.36$ reduction coefficient from flat to cylindrical surface.

Let us now calculate the percentage of the *albedo component that invests the cylinder in shade.*

Solyndra datasheets declare an amount of albedo of 23.9%[13] when the system is fully operational. However, considering that the rooftop of the

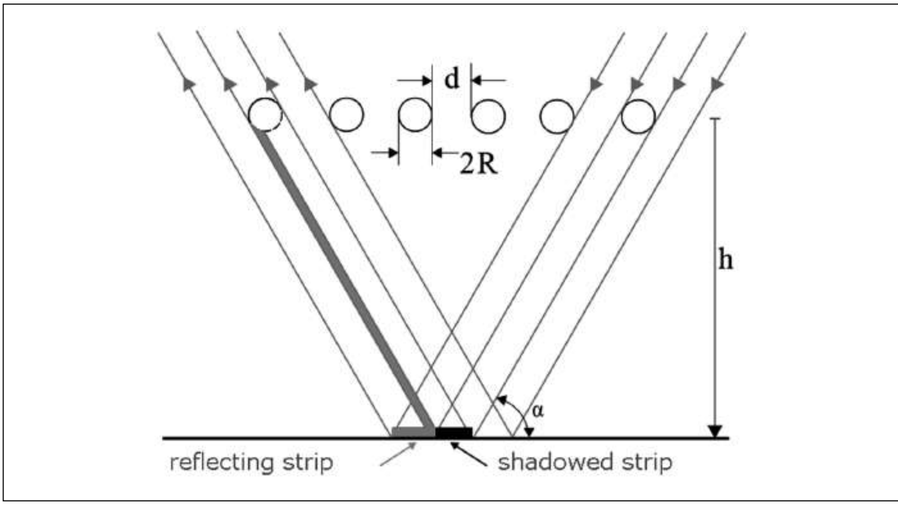


Figure 15.

Hessiana building is not a highly-reflecting total white surface, this value should be considered a higher limit.

By substituting in (9) I + D = 0 and dividing the total reflected radiation between its direct and diffuse components $R = I_r + D_r$, we obtain:

$$G_{shd} = I_r + D_r \qquad (12)$$

Since the quantity of the two components depends on the size of the reflecting surface (see in Figure 7 the array of cylinders producing strips of shade over the surface), the ratio between total surface and shadowed surface S/S_{shd} needs to be evaluated. Firstly we need to introduce two simplifying hypotheses:
a) the diffuse component reflected by the shaded strips is negligible;
b) the surface below cylinders is perfectly flat[14].

A possible distribution of the reflected rays over the year is shown in Figure 15 (not in scale and only meant to provide support to the intuition) where h = 30 cm and d = 3.5 cm. Under the cylinders, reflecting and shadowed strips shift their position over the year and change their surface ratio. Let us calculate the surface ratio at a particular time of the year.

The surface in shade produced by the cylinders' shadow is easily calculated with the formula $S_{shd} = 2R/\sin\alpha \cdot L$ with $R = 1.1 \cdot 10^{-2}$ m e L = 1 m. This value is subtracted from the total area under the cylinders $S = (d + 2 \cdot R) \cdot L = 5.7 \cdot 10^{-2}\ m^2$ approx. The percentage of reflecting area is given by $k_{Su} = (S - S_{shd})/S = 1 - 0.386/\sin\alpha$. Figure 15 also shows the direct component being partially reflected by the semi-cylinder in shade, so if the α angle increases the reflecting surface decreases and vice versa[15].

So to calculate I_r we conclude that

reflection of direct radiation only affects a part of the semi-cylinder, on account of the shadows and of dispersion through the gaps between the cylinders. If I is the direct component of light reflected from a perfectly-mirroring surface on an isolated cylinder, then this restriction applies:

$$I_r < I \qquad (13)$$

where I_r is the component of direct radiation falling on the cylinder exposed to reflection.

The difference $\Delta I = I - I_r$ depends on the amount of albedo and on the inclination of sunrays. The component I_r, considering the intensity of reflected radiation to be proportional to the reflecting surface, is given by:

$$I_r = k_{Su} \cdot k_S (G - D) \qquad (14)$$

where $I = (G - D)$, valid for specular reflection. Substituting $\alpha = 45°$ (the latitude of Talmassons at the equinox where $\gamma = \alpha$) and with $k_{Su} = 0.45$ approx., we obtain the result of $I_r = 0.033$ G and in percentage $I_r\ \% = 3.3\%$ G approx.

The other component D_r is given by:

$$D_r = k_S\, k_{Su}\, k_{dif}\, \rho(1 - \cos(180 - \gamma))/2\ G \qquad (15)$$

and if $\rho = 0.7$[16], then $D_r\% = 0.027$ G and in percentage 2.7% G.

So the proportion of global solar radiation falling on the semi-cylinder in shade is:

$$G_{shd} = I_r + D_r = 0.033\ G + 0.027\ G \cong 0.06\ G = 6\%\ G \qquad (16)$$

Therefore, the variation percentage in radiation over and under the plane compared with total radiation is:

$$G_{cyl} = G_{ill} + G_{shd} = 0.06\ G + 0.23\ G \cong 0.3\ G = 30\%\ G \qquad (17)$$

We must take into account that the albedo component is not intercepted by the rear of a flat module of equivalent area to the cylindrical module because it is obscured by the protective black coating, so the total radiation G must be reduced by this component. The G_m radiation measured on the plane becomes:

$$G_m = G - D_r \cong 0.97\ G \qquad (18)$$

In conclusion the variation percentage will be:

$$\Delta G = G_m - (1 - G_{cyl})\, G = 0.97\ G - 0.62\ G = 0.34\ G \text{ or } \Delta G\% = 34\% \qquad (19)$$

and so to calculate the radiation being effectively distributed on the cylinder we must subtract about 34% from the measurement obtained on the tangent plane, so that the original 950 Wm^{-2} is reduced to the value of 627 Wm^{-2}.

This example is significant in that it shows that it is fairly difficult to pass the performance test and that in order to reach 900 Wm^{-2} at midday we need to have favourable weather conditions; although we are helped by the fact that the solar meter will be facing the sun and that it is easy to find values approaching 1000 Wm^{-2} at sea level at a mid-European latitude. In addition, the surface of the rooftop needs to present excellent reflecting properties in order to mirror the albedo component; the better reflecting is the white paint of the surface, the closer the measure to the ideal condition expressed by the above equation.

Several tests were carried out on site on testing day. In one of these, as we shall see, we managed to surpass the threshold value of 600 Wm^{-2}, measuring more than 900 Wm^{-2} on the plane of the solar meter. The coefficients and data used in (19) and yielding a result of 34% will presumably need to be adjusted if the tests are carried out at other times of the year. We also need to consider that measurements taken in the open air are affected by environmental conditions (such as ventilation, humidity, and air temperature) and also by the time it takes the operator to process the measures collected. So the theoretical result which we have found, and which has been confirmed by testing, should be seen as indicative, with a certain possibility of error.

In the next paragraph we will outline a method to measure the radiation intensity distributed around the cylinder with a specially manufactured circular solar meter[17]. The reading constant of the circular solar meter has been calculated through a process of calibration.

5. Experimental method for a calculation of the distribution of global radiation in flat and cylindrical surfaces. To estimate the global radiation along the circumference of a cylindrical surface we have moved a small PV cell along the circumference at discrete steps of 15°; at each step electrical current has been measured by a multimeter, then converted into radiation intensity by multiplying the current per a conversion constant. The results are reported in Table 1.

Measures were collected over a period of about 15 mins (the first measurement was taken at 15:50, the last at 16:05).

At the beginning of the measurement session, the solar meter displayed an intensity of 664 Wm^{-2} and at the end a value of 651 Wm^{-2} with an accuracy coefficient of ± 5%. The mean of the measurements reported in the penultimate column is G' = 494 Wm^{-2}.

The data were collected on 15 August around solar noon. On that day, at the latitude of Talmassons[18], the angle of solar rays on the horizon was about $\alpha = 60°$ (tilt $\gamma = 30°$).

At this point, we are able to determine the percentage variation between the radiation measured on the plane at the angle of tilt $\gamma = 30°$ ($G_{ill} = 971\ Wm^{-2}$) and the weighted average of the values reported in the penultimate column of Table 1 (G' = 522 Wm^{-2}), which is approximately 46% with a 26% deviation from the value of 34% calculated in (19). This percentage deviation from the theoretical value is rather marked, but could be reduced if we consider the rather poor albedo component ($\rho < 0.7$) due to the characteristics of the terrace on which measurements were collected; moreover, the reading constant of the solar meter[19] in Table 1 is probably closer to the

Table 1. Measurements of light intensity along the circumference.

Number of measure-ments	Cell inclination	Short circuit current	Radiation intensity on cell	Temperature Circular solar meter constant: $k = 2.75$ mA/(Wm^{-2}) ± 10% Cylinder orientation: East-West	Air temperature T = 36°C
N	**Degrees**	**Isc(mA)**	**Wm^{-2}**	**NOTE**	
1	0	313	861		
2	15	345	949		
3	30	353	971		
4	45	357	982		
5	60	343	943		
6	75	309	850		
7	90	281	773		
tot		6328	G' (Wm^{-2}) average	904	
1	105	234	644		
2	120	193	531		
3	135	149	479		
4	150	161	454		
5	165	174	443		
6	180	165	429		
tot		2959	G'(Wm^{-2}) average	497	
1	195	156	410		
2	210	148	407		
3	225	135	371		
4	240	123	338		
5	255	110	303		
6	270	100	275		
tot		2123	G'(Wm^{-2}) average	351	
1	285	81	223		
2	300	77	212		
3	315	61	168		
4	330	57	157		
5	345	135	371		
tot		1130	G'(Wm^{-2}) average	226	

minimum value of $k - 0.1\,k$. With this value, the deviation limit of 26% would be halved.

Similarly, when we estimate the percentage variation between the measures taken along the arcs of the

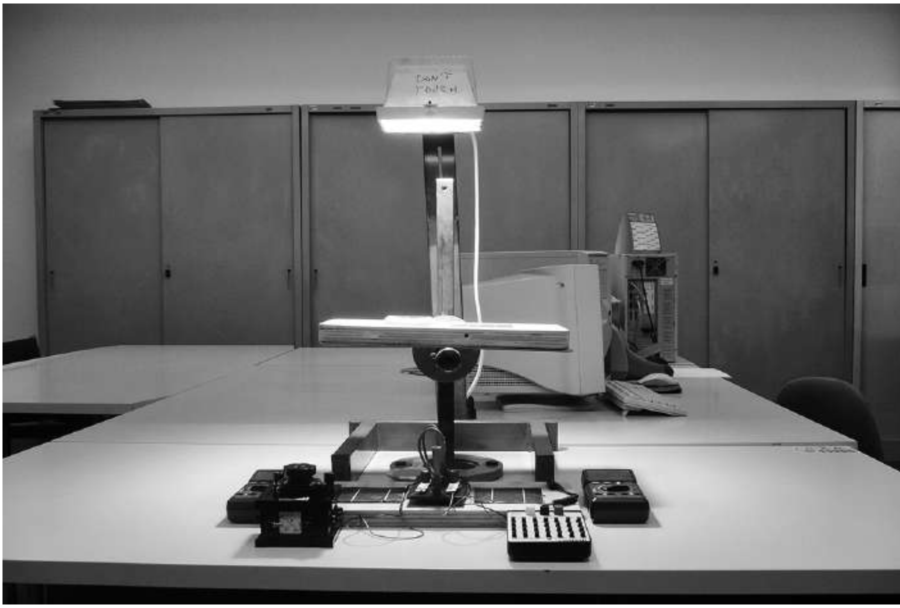


Figure 16.

semi-cylinders in the light and in the shade, relatively to the two intervals written below:

semi-cylinder in light
$330 < \alpha \leq 120$ (0)
semi-cylinder in shade
$120 < \alpha \leq 330$

with G_{ill} = 686 Wm^{-2} the mean value calculated on the first interval and G_{shd} = 353 Wm^{-2} the mean value calculated on the second, we obtain a variation of approximately 48.5%. Conversely, if we consider the difference between G_{ill} = 23% G found in (11) on the semi-cylinder in light and G_{shd} = 6% given by (16) on the semi-cylinder in shade found in (16), we find a percentage variation of 73.9% with a deviation from the values of Table 1 of 34.4%. This striking difference is explained by the fact that the measures of Table 1 were taken on a single cylinder, which does not suffer the effects of shadowing from other cylinders, whereas in a real situation cylinders are assembled in a rack.

To these considerations we add the following.

Experimental measure integration was rather approximate (24 steps with a silicon wafer covering a hexagonal polyhedron); a greater number of steps would lead to a more precise result. Moreover, photo-induced current in a PV cell depends on the spectrum of light and, while direct sunlight has all the radiation frequencies of a black body, the spectrum of reflected light varies depending on the portion being absorbed by the surface coating. On the other hand, our theoretical procedure also presents limitations as it is based on statistical data – in particular, the value of the albedo component can vary significantly in relation to the reflective properties of the surface coating.

6. Performance tests. A PV system in its simplest architecture is composed of two subsystems: a direct section where light power is converted into electrical power (dc side) and a conversion section where electrical direct power is transformed in alternating power (ac side).

Before starting the test[20], we carried out a prior verification. A voltage meter and an amperometer were connected to the input (dc) side of an inverter, while two of the same were applied to its output (ac) side; the inverter, in turn, was connected to the west-facing PV subfield[21].

The measurement of radiation intensity was carried out in two stages: a solar meter, provided by Hessiana srl, was first exposed outdoors, facing the sun, and then indoors, in a cubicle where the two inverters were housed, facing a xenon lamp. A pyranometer was mounted on a moving device (Figure 16), so that we could change its tilt angle and/or its distance from the lamp, therefore varying the incidence of light on the sensor.

Having measuring the intensity of direct solar radiation, we positioned the pyranometer under the xenon lamp and scaled down the intensity measurement. The values obtained were transmitted to a processing unit which displayed the results on a screen. After running several tests, an overall performance of at least 75% was verified, confirming the hypothesis that the system's real power was greater than the nominal power declared by the manufacturer.

The test also showed that the system's overall performance exceeded the threshold value of 75% even when it did not pass the limit of 85% on the dc side, where the efficiency of the conversion of radiant solar power into electrical power is evaluated. This is explained by the formula for the overall performance:

$$\eta = \eta_{dc} \cdot \eta_{ac} \qquad (20)$$

Efficiency on the ac side (η_{ac}) always tested positive because inverters automatically maintain an efficiency that exceeds 95%, so even with an efficiency of less than 85% on the dc side (η_{dc}) it was possible to pass the overall threshold of 75%. In our case, we managed to reach both efficiency thresholds only by decreasing the radiation intensity on the surface of the sensor positioned perpendicularly to the solar rays.

Considering that CEI standards require that tests should be performed with an intensity greater than 600 Wm^{-2}, we needed a solar power of around 900 Wm^{-2} on the cylinders if we wanted to pass the test. So outdoor measurements had to be carried out around midday on a sunny day.

The data recorded by the processing unit SOLAR-300 / HT303 provided by Hessiana srl are as follows:

P_{dc}	= 22.27 kW	P_{ac}	= 21.24 kW		
η_{dc}	= 0.87	η_{ac}	= 0.95		
V_{dc}	= 560 V	P_f	= 0.961		
I_{dc}	= 40.48 A	V_{AC1}	= 419.6 V	I_{AC}	= 30.57 A
I_{rr}	= 476 Wm^{-2}				
P_{nom}	= 50.57 kW	V_{AC2}	= 419,12 V	I_{AC2}	= 31.9 A
T_{PV}	= 36.5°C				
T_{INV}	= 33.6°C	V_{AC3}	= 420,2 V	I_{AC3}	= 29.97 A

In this specific case I_{rr} = 476 Wm^{-2} is less than 600 Wm^{-2} and so the test only served to validate the working hypothesis.

Performance testing according to the guidelines of CEI 82-25 should be a requisite of all PV plants, since it provides a practical verification of the manufacturer's declaration of compliance.

It is well known that in PV plants connected to the electrical grid the ac output of the inverter supplies power to local electrical loads or to the public network (in Italy managed by ENEL). In this particular plant, the converter was composed of two three-phase IGEATEAM inverters connected in parallel to two PV subfields (see Figure 17) including the same number of modules and arranged in gently sloping rows facing respectively east and west. The cylinders' axes were also oriented in an east/west direction (see in Figure 18 the magnetic needle oriented from north to south, perpendicularly to the cylinders' axes). Since the rows were slightly inclined in opposite directions the production of the two subfields was a little different in the early hours of the morning and at the end of the afternoon. A first trial test was carried out on 16 October 2012 at one o'clock in the afternoon (corresponding to solar noon) with 75% relative humidity and 17.4°C air temperature. The inclination of the sun was 37° above the horizon, approximately 8° less than the latitude.

The input data collection was carried out by an HT303 pyranometer with the storage unit SOLAR-01; a Mac Solar solar meter was used to check the radiation constant and the inclination of the support, in order to reduce the radiation intensity by the necessary amount (see the photograph in note[19]).

Testing was finally carried out on 24 October 2012 at 12:45, under ideal weather conditions[22]. The processing unit SOLAR-300 was attached to the inverter connected to the west-facing PV field. After synchronisation with the unit SOLAR-01, we measured the intensity on the plane lying perpendicularly to the sun rays and adjusted the inclination of the support stand in Figure 16, obtaining a 30% reduction in intensity on the

Figure 17.

Mac Solar display. After a few minutes SOLAR-01 was connected to the processing unit SOLAR-300 located in the inverters compartment. The results are shown in Tables 2 and 3.

Positive results were obtained on both the dc and ac sides, with a 33.9% intensity reduction and a difference from the calculated value of around 3%.

Temperature was measured with a PT 100 thermocouple positioned in the air (in flat modules the probe is applied to the back of the modules as per instruction of CEI 82-25) in order to verify that air temperature was kept much lower than 40°C, value indicated by CEI 82-25 for corrections in the temperature of the power supply. However, it is very unlikely that PV cylinders can reach such a high temperature, as they are partially shaded and continuously ventilated, so this measure had no impact on the outcome of the test. The Eff-DC value of 609 ÷ 610 Wm^{-2} was slightly above the minimum, while radiation intensity on the plane was much greater.

The connections of probes and sensors are shown in Figure 19.

In conclusion, only reducing the intensity of radiation on the plane, as it has been theoretically demonstrated with measurements in the open air, the processing unit could give positive results within the constraints of CEI 82-25. A more exhaustive research on the performance of PV cylindrical modules should be repeated several times over various days under conditions of low and high irradiation and at different hours of the day. This task should be assigned to a

Figure 18.

specialized laboratory which should install a PV cylindrical system with automatic data-collecting for continuous monitoring[22].

7. Final considerations. This study has deliberately not considered and evaluated the overall yield of the PV plant over time, i.e. the Equivalent Solar Hours (ESH), that is the number of solar hours when the system works at its rated power, the Energy Pay-Back Time (EPBT), that is the return time of the energy used for the production of the plant itself, and the Financial Pay-Back Time (FPBT), that is the time needed to match the investment made by the customer. The promotion of a PV system on the basis of its efficiency (performance) under STC may not be the marketing strategy determining the success of a solar technology.

Regarding this aspect, the owner of a PV plant, called "responsible subject" by GSE, the Electrical Services Operator that for a period of twenty years guarantees a financial incentive in euros per kilowatt hour produced (€/kWh), may positively evaluate the investment in the long period, taking into account the cost of the plant (€/Watt) and the Balance Of System (BOS), that is the cost of a PV system excluding the panels. The decision by Hessiana srl of installing Solyndra PV modules was mainly based on BOS, also because it was not possible to drill the roof of the building or load it with heavy blocks in order to install conventional flat modules.

Regarding the concept of efficiency, I think we need to clarify the substantial difference between the yield of

Table 2. Light intensity measured by the two solar meters.

Mac SOLAR	930 Wm^{-2}	±5 Wm^{-2}
HT303	4.3 mV /7 mV/1kW m^{-2} = 615 Wm^{-2}	±0.5 mV

Table 3. SOLAR-01 measurements.

Irr_Avg [W/m²]	Irr_Max [W/m²]	Irr_Min [W/m²]	TC_Avg [°C]	TC_Max [°C]	TC_Min [°C]
610	610	609	30.9	30.9	30.9
610	610	610	30.9	30.9	30.9
610	611	610	30.9	30.9	30.9
610	611	610	30.9	30.8	30.7
610	610	609	30.6	30.6	30.5
	Eff_AC		Eff_DC	PRP	
	0.937		0.868	0.813	
	0.937		0.867	0.813	
	0.937		0.867	0.813	
	0.937		0.868	0.813	

a PV plant and its efficiency/performance with reference to CEI 82-25, as the two concepts are easily confused. So the functional testing of a PV plant is the measurement of efficiency in a particular instant in time, while yield is performance over time as expressed by the ESH parameter, that we now define precisely with a formula:

$$ESH = E/(P_n \cdot dd) \qquad (21)$$

where E is the energy produced in a number of days (dd) and P_n the rated power.

The energy measurement is given by the integral calculation of the instant power according to the formula:

$$E = \int \cdot \varepsilon(t) \cdot J(t) \cdot S \qquad (22)$$

It shows that the total energy production depends on instantaneous efficiency ε(t), that is the amount of electric power (W) converted from intensity radiation (W m^{-2}) extended to the whole surface S (m^2) of the PV plant.

In all grid-connected PV systems the inverter maintains the highest possible peak power P_{mp} in all weather conditions, so we obtain the maximum efficiency condition in energy conversion. The difference between the energy produced at STC efficiency and the energy recorded by the ENEL meter is:

$$\Delta E = \int \cdot \varepsilon_{STC} \cdot J(t) \cdot S - E \qquad (23)$$

which can be considered a quality indicator for the evaluation of a PV plant performance.

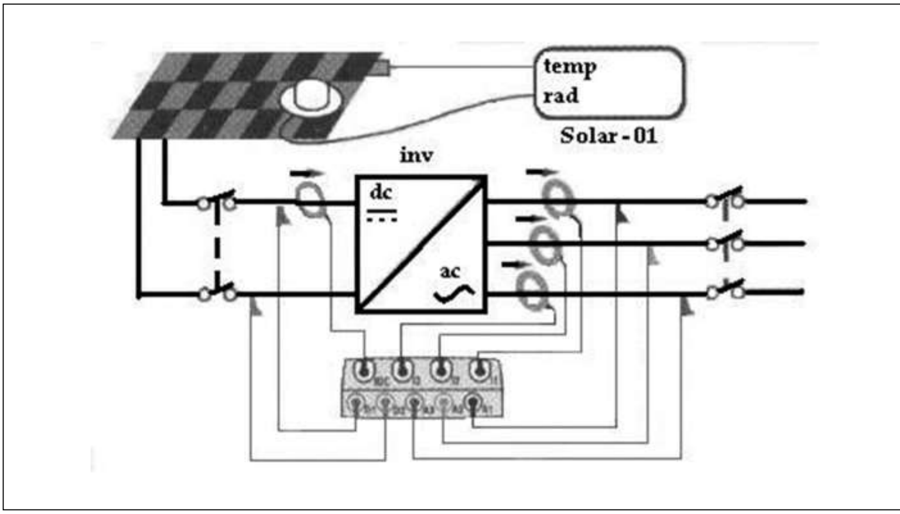


Figure 19.

On a financial level the quality of an investment can be evaluated by the formula:

$$\Delta = ESH{\cdot}P_n{\cdot}dd{\cdot}R_u - C_u{\cdot}P_n \quad (24)$$

where R_u denotes revenue from government incentives €/kWh (constant over twenty years) taking into account all costs; and C_u is the unitary cost of the PV plant in nominal €/kW. When the delta sign is negative there is no return of investment, when it is positive there is a gain.

The value of ESH, depending on the relative reduction of efficiency over time, greatly affects the delta value. It is the difficult assessment of this parameter that makes an estimate of delta values very problematic, and in fact no manufacturer provides data on efficiency over time. IEC 61646 (and likewise 61215) prudentially certifies a degradation of efficiency of thin-film modules of no less than 90% in the first ten years and no less than 80% in the following 15 years. This parameter is particularly critical in the case of Solyndra cylindrical modules that are certified by their rated power within a range of negative and positive uncertainty. Competitive factors are pressing manufacturers to offer modules with positive tolerance, i.e. with minimum power guaranteed.

Solyndra entered the European market certifying cylindrical CIGS thin-film by the same standard used for flat modules. This because of the lack of official guidelines on how to evaluate the efficiency of a PV cylinder in STC, considering that half its surface is not directly hit by radiation. The company's choice was to indicate a nominal power referred to approximately half the PV surface.

If rated power had been measured

by irradiating a flat surface equivalent to the entire lateral surface of the cylinders, their rated power would have been greater than the real one and the modules would have produced a lower yield than flat modules. The decision to certify the power of a flat surface equivalent to the area of a semi-cylinder has the same meaning as offering a "positive tolerance". If the display of the two inverters does not show an electric power higher than the rated power of 115.20 kW in near STC, it is because of the low dc side conversion efficiency that rarely exceeds the threshold of 85%.

Shifting the focus from a technological field to a financial one, the purchase deal would appear to be favourable to the customers, who pay for less PV surface than they actually get, and spend less €/W than they would have paid for a thin-film or crystalline plant of the same rated power. So how could Solyndra afford the greater cost of using more PV material than they would have used to produce a flat module of the same rated power, and at the same time think of selling a competitive product? We can presume that they anticipated to balance the higher €/W cost of PV material with scale factors in the production cycle; in a nutshell, a greater production of cylinder panels than flat modules of equal power. The high performance combined with a competitive BOS would have quickly replaced the thin-film CIGS flat modules with cylindrical ones, at least on the flat roofs of industrial buildings, yet something went wrong.

The most credible explanation concerns the trend in thin-film and crystalline-silicon prices. Solyndra might have expected on the one hand a rapid fall in the production price of CIGS film and on the other a stability in the cost of crystalline silicon. Both predictions did not occur. The most important factor must have been the plummeting €/W prices of crystalline silicon.

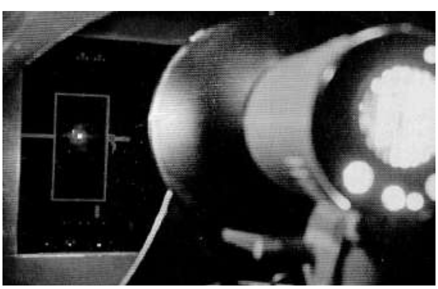
A definitive verdict on the performance of cylindrical thin-film technology can arise from the results of the numerous PV plants built by Solyndra around the world, but also from the presence of standard procedural guidelines. This should improve research and innovation and also provide testers with clear indications on how to measure the efficiency of a PV cylindrical system. Yet at the moment Solyndra is in receivership and production is permanently halted.

[1] CIGS means Copper Indium Gallium (di)Selenide; in a laboratory, the performance (efficiency) of this PV heterojunction can reach up to 20%. The PV cylinder was lent to me by Daniele Della Toffola of the regional environmental agency ARPA Friuli Venezia Giulia, located in Palmanova, near Udine.

[2] We will preferably use the term "performance". For the same concept CEI 82-25 uses the terms "efficiency" and "yield"; in the present issue we will mainly use 'efficiency' while yield is more properly efficiency/performance over time and expresses the energy production of the PV generator. From a quantitative point of view, efficiency or performance is a numeric value that indicates the percentage of solar radiation power (Wm^{-2}) being converted in electric power (W).

[3] Solyndra datasheet reports for each PV cylinder the following data: P_n = 5 W with power tolerance of ± 4%; V_{mp} = 91.7 V; I_{mp} = 50 mA; V_{oc} = 124.6 V; I_{sc} = 59 mA.

[4] The peak or rated power of flat modules in Standard Test Conditions (STC) is defined by IEC 61646. It is measured in a darkroom by a solar simulator: a module is placed in a vertical position against a wall; in front of it a xenon arc lamp flashes perpendicularly to the plane of the module. See below the photo of a solar simulator in the Esti Ispra laboratories (Rutschmann 2009). In our test, the solar simulator was calibrated to deliver the equivalent of 1000 watt per square meter (Wm^{-2}) of sunlight intensity, with a cell temperature of 25°C (77°F) and a Mid-Europe air mass (AM = 1.5); a computer processed the data and calculated the power rating (or power peak because radiation at sea level does not exceed this value). If the rated power of a Solyndra module were measured by placing a cylindrical panel against the dark wall, then the surface of irradiation of a cylinder would be approximately half its total surface (i.e. the surface of the tangent plane in front of the xenon lamp), and consequently the electric power would be lower than the real power measured in an outdoor situation close to STC, because of the albedo component that increases the solar radiation intensity.



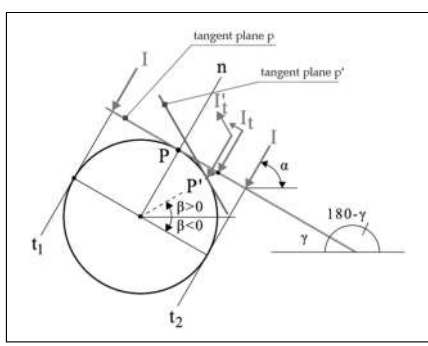
Solar simulator.

[5] Later we will consider the situation around solar noon, when sunrays fall perpendicularly to the cylinder axis; at times when sunrays have an angle different from 90°, the consideration remains valid if we take into account only the normal component of the solar radius, disregarding the tangent as it produces no PV effect.

[6] From this point forward, "unit intensity power" and "density power" are used interchangeably within our text; in equations, however, we indicate with I the power intensity (W) and with I / S the power density (Wm^{-2}). So if we say that power (W) moves entirely from the *a – a* to the *a' – a'* plane, power density (Wm^{-2}) decreases if the surface increases and vice versa.

[7] The phenomenon of diffuse light is called "Rayleigh scattering" and takes place when a light wave encounters particles smaller than its wavelength. It can occur when light travels through an essentially transparent medium, mostly gas and liquids; in Italy the density of diffuse radiation on a beautiful cloudless day varies from 15% to 25% of global radiation. In this text we have chosen a reduction value of k_{dif} = 20%; the choice was not inspired by any particular criterion other than the Aristotelian ethics summarised by the Latin motto "in medio stat virtus", which translated into technical language means that the most likely value is the average of the lower and upper limit values.

[8] See in the Figure below the situation with sunrays inclined at an angle $\alpha < 90°$ on the plane of the horizon and a plane p tangential in P to the circumference of the cylinder lying on an east-west axis and inclined by a γ tilt angle. The Figure also shows the sweep angle β with a positive sign along the counter-clockwise arc until t_1 and a negative sign in the opposite direction along the arc until t_2. The following theorem can be demonstrated: given a bundle of parallel lines t between t_1 and t_2, with t_1 and t_2 belonging to the bundle, intersecting the tangent plane p, the value of the tangent component I_t of I along the



Sun rays with random direction.

plane is always less than the value of the tangent component I'_t of I at the current point P' of the tangent plane p' along the semi-circumference, if and only if $\alpha = 90 - \gamma$, that is if the direction of I is perpendicular to the tangent plane p. Consequently the corollary follows: if $\alpha \# 90° - \gamma$ an arc of circumference $\hat{C}$ exists where $I'_t < I_t$ is true, and moreover the length of the arc($\hat{C}$) is smaller than the length of the arc 180° – arc($\hat{C}$).

[9] A value of 20% was found in a typical situation at the Fraunhofer Institute (statement from Solyndra datasheet).

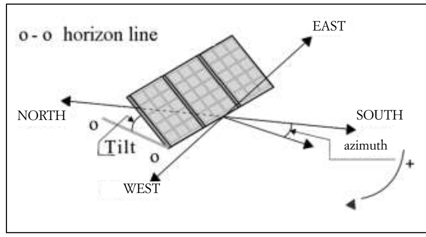
[10] Cell efficiency is not clearly reported in the Solyndra datasheet, which gives a ratio of 12% ÷ 14% electrical output to incident solar power, but this is referred to cells on a plane and not to those arranged along the axes of a cylinder. These data are in line with what declared by the manufacturers of CIGS modules; one manufacturer, for example, declares $P_n = 36$ W, $S = 0.54 \cdot 0.954$ m^2 yielding a value of approximately 13.5%. The efficiency of flat PV modules is measured by uniformly exposing a module to black body radiation (solar radiation has a very similar spectrum outside the atmosphere to black body radiation) under STC. Data are automatically processed, the point of maximum power (nominal power) is determined, and efficiency is calculated according to the equation (5). If the nominal power of a Solyndra panel (or cylinder) were to be established by irradiating it with light against the wall of a darkroom in a solar simulator, this value would only refer to half the surface of the cylinder (equating the curved surface of the semi-cylinder to the tangent plane as viewed by the xenon arc lamp). In these circumstances the nominal power could also be calculated by dividing the nominal power of a certified CIGS film by two.

[11] The calculation has been carried out on a spreadsheet with steps of 0.1 tenth of a degree; the equations have been split into the two parts of a semi-circumference, with every step of the calculation giving the normal component value:

– $\sum I \cdot \cos(90 - \beta)$ current angle: $0 < \beta < 90$

– $\sum I \cdot \cos(\beta - 90)$ current angle: $90 < \beta < 180$.

[12] The angle between the horizon and the plane of a module is called tilt angle. At solar noon (azimuth equal to zero) the sunrays hit the surface of the module perpendicularly; if $\gamma = 90 - \alpha$ the radiation intensity vector has no tangent component (maximum intensity penetrates the module).



Tilt and azimuth angle.

[13] A white-painted roof covering is not a specular surface, so light is partially absorbed (producing heat) and diffused (surface irregularities are much bigger than the wavelength of light). If we apply the surface correction factors to the value of the albedo component, we obtain a figure which is similar to the value determined by (16).

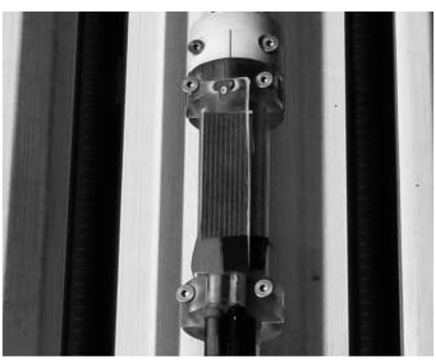
[14] The Hessiana building has a gable roof facing east/west with a 5° pitch approximately (Figure 17). Its concrete slab has been covered by a trapezoid iron sheet which produces a reflection depending on the position of the sun that is very difficult to calculate. In the definition of the albedo component ideal for PV production, the manufacturer does not distinguish between the various types of roof covering, but merely recommends that it should be painted white. This absence of indications, together with the fact that in our own experience different types of roofing do not determine significant differences in PV production, have convinced us to transpose the results obtained with an ideal flat roof to a trapezoid surface.

[15] Shadows are longer when the sun is very low on the horizon, and they are shortest near the Summer equinox at noon.

[16] The factor $\rho = 0.6$ is taken from reference tables and corresponds to white-painted masonry walls.

[17] The circular solar meter is composed by a polycrystalline PV cell specifically cut and mounted on a slide able to move along the circumference of the cylinder. Two red and black wires connect the PV cell to a multimeter. The fixed part is marked with some notches that show the angle step. The circumference has been divided in 24 parts (a step angle measures 15°). The constant of the circular solar meter was calculated by comparing electric current intensity and radiation intensity measured by a solar meter provided with

a monocrystalline sensor cell and a display (in the photograph the circular solar meter is connected by two wires to the multimeter installed around a cylinder on the roof of the Hessiana building). A PV cell solar meter is based on the law of proportionality between the current produced by the cell (mA) measured with a digital instrument based on the Ohm law (multimeter MD320) and the intensity of solar radiation (Wm^{-2}). This constant has been determined after several measurement sessions taking place on different days and at different times of day. The current measurement by a circular solar meter has been compared with radiation measurements by two solar meters: a Mac Solar SLM018c-3 based on a PV effect and an HT303 pyranometer based on a thermoelectric effect. The solar meter based on a PV effect has a much quicker response than the thermocouple-based pyranometer and for this reason we have introduced an uncertainty in the definition of the constant: $k = 2.75 \pm 10\%$ (Wm^{-2}/mA). The circular solar meter has been constructed at the department of mechanical engineering of ITI "A. Malignani" (now ISIS "A. Malignani"), Udine, by the technician Salvatore Ravo following general indications by the author of this text.



Circular solar meter.

PV cell solar meter (left), thermocouple pyranometer (right).

[18] The height of the sun at our latitudes of the Northern hemisphere is given by the formula: α = declination + latitude. The height of the sun at the latitude of Talmassons and at a declination of 13.83° is approximately $\alpha = 45.9° + 13.5° = 59°$ (see http://www.ilpaesedellemeridiane.com/simulatori/04noz/08altezzasole.htm).

[19] The solar meter Mac Solar SLM018c-3 directly displays the value of Wm^{-2}; it is based on the experimental evidence that the intensity of light that strikes a monocrystalline cell is proportional to the photo current produced. The pyranometer HT303 is an application of the thermoelectric effect (also known as Seebeck effect), which generates a voltage in the millivolt range when the junction of two metals is exposed to the sun, producing a temperature difference. Solar radiation intensity is calculated by multiplying the mV by the constant of lecture $k = 7$ mV/kWm^{-2} given by a lab calibration service. We first established the time of day when the two solar meters had the greatest proximity of data (the Mac Solar has a sensitivity dependent on wavelength of light while the pyranometer keeps it constant). We found that the solar meters gave similar indications around solar noon, in other words for values of the azimuth angle close to zero, with a percentage of accuracy of ± 10%. The calibration operation in the open air was problematic because air mass movements, even at a high altitude and with a clear sky, affect the measures displayed by the Mac Solar, while they do not have an influence on the workings of the pyranometer, on account of its inherent inertia.

[20] Before and during the test, I was assisted by Aldo Moratti of Hessiana srl, whose contribution was crucial for the on-site testing and measurement procedures.

[21] Given that the two PV subfields comprised the same number of modules and around solar noon they produced approximately the same electric power, only one of the two inverters was used in the test.

[22] We are going to provide further indication that

the PV plant on the Hessiana building produces electricity with an efficiency comparable to other similar plants with flat modules by considering only half of the PV surface of its cylinders. For this, we need to verify that the PV plant provides at least the rated power certified by the manufacturer in accordance with CEI/EN 61646. On 7 September 2012 at 12:20 the two inverters gave the following measures on the dc side: $P_{dc,\ East}$ = 34.6 kW and $P_{dc,West}$ = 32.4 kW, for a total of P = 67 kW. The PV cell and the thermocouple solar meters were placed on a tangent plane perpendicular to the solar rays and the values displayed, having subtracted 30%, were respectively $I_{r,\ Mac\ So}$ $=^{lar}$ 673 Wm^{-2} and $I_{r,\ HT303}$ = 695 Wm^{-2} with an uncertainty of ± 5% and ± 3%. The calculation of efficiency given by (7) yielded a value of $\varepsilon\% \cong 8\%$, slightly higher than the theoretical one at STC using half of the cylinder surface [(see the calculation developed with reference to the formula (5))]. In fact, setting a slightly lower yield value than the one showed in Table 3, the plant produces a little more energy than the amount certified. It is well justified to claim that this extra production comes from the component of albedo that invests the other half of the cylinder surface.

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A son stadis consultadis ancje chestis pagjinis web / *The following web pages have also been consulted*

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– www.meteo.fvg.it

La agjenzie ARPA OSMER dal FVJ e furnìs i dâts meteo storics dì par dì e mês par mês / *ARPA OSMER provides daily and monthly weather records for Friuli Venezia Giulia*