Feasibility for the use of Flat Booster Reflectors in Various Photovoltaic Installations

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Feasibility for the use of Flat Booster Reflectors in Various Photovoltaic Installations

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Abstract- The feasibility for the addition of flat booster reflectors to PV panels is techno-economically investigated for various applications (building attached PVs, ground installations, grid-connected or stand-alone units) and various PV types (mono-crystalline and amorphous silicon PV panels). A model developed to this aim is applied to optimize the parameters of the PV/reflector module and to evaluate its applicability according to the solar radiation data of Athens (Greece). The reflectors may lead to significant increase of total incident solar radiation annually, without however to equivalently improve the economy of the system. The several reasons for this are identified (uneven illumination, edge effects, increased cell temperature, cost of reflectors). Promising applications of flat booster reflector proved to be their use in specific building attached photovoltaics (at south facades) and in standalone applications, allowing –in the latter- a better matching between the load and the energy source annual profiles.

Keywords- Photovoltaics; Photovoltaics in buildings; Solar energy management; Booster reflectors; Stand-alone applications.

1. Introduction

The feasibility of solar radiation augmentation by the use of flat booster reflectors was investigated for solar thermal converters a few decades ago with positive results [1,2]. Similarly encouraging prospects were later announced for photovoltaic (PV) panels, too [3], for which their higher cost renders solar radiation augmentation even more important.

Experimental results with various arrangements (see Fig. 1) and from different sites worldwide have indeed proved the boosting potential of flat reflectors [3,4,5,6,7], reporting annual electrical yield increment to range from 10% up to 30%, and a respective increase of total equipment cost by 10% only. The effect to the electrical yield proved to depend on several factors such as the specular and diffuse reflectivity of the reflector, the reflector to PV panel width ratio, the local solar radiation data, the latitude of the site, shading and uneven illumination caused by the reflectors, the ambient temperature and the probably consequent overheating impact.

For the climate of Sweden and for a reflector with a width 2.5 times that of the panel (arrangement of Fig. 1a), an 8-17% annual increase of the evenly distributed radiation was realized, when the width of the reflector varies from 2 to 5 times the width of the PV panel [3], while the total radiation increase (including uneven illumination) reached 24%. As a consequence, the potential advantages by either selecting thin film PV modules (instead of crystalline silicon cells), or by appropriately modifying the interconnections between the cells of each panel -to get the most benefits for the cases where the reflected illumination is unevenly distributed on the panel- were highlighted.

For the city of Tokyo it was concluded [7] that solar radiation concentration may reach the value of 1.5 at the solar noon, by simply installing perpendicularly to the PV panel a reflector having 2.7 times the width of the panel. The application of two reflectors in a PV/Thermal system (trough arrangement, see Fig. 1.d) was investigated in [6], and found for the city of Nis (Serbia), that incident radiation may increase by more than 65% in mid-August, leading to 17% increase of electrical energy yield.

In relevant experimentation in Iran, with a photovoltaic (PV) water pumping system equipped with reflectors [8], it was found that output power from the PV panels increases by 14% with the use of aluminium foil reflectors, but when a stainless steel 304 reflector was used instead, this increment was restricted to 8.5% only.

Due to their apparent benefits and simplicity, flat booster reflectors placed in between the arrays of PV panels (as per Fig. 1.b) have already been commercialized in the U.S.A. for roof installation. Special reflectors have been developed to this aim, incorporating valuable characteristics like (i) low UV reflectivity (to avoid overheating and ageing of the PV panel) and (ii) hydrophilic coating to succeed self-cleaning [9]. Furthermore, a manufacturer in Minnesota produces specialized panels traded under the name “redundant array integrated solar” RAIS [10], with their solar cells assembled in a parallel matrix allowing in this way more use of unevenly distributed irradiance. The company offers her proprietary reflectors together with the panels, asserting that they lead to 20% higher electrical yield per installed capacity in roof installations [11].

In Europe the technique is still at the demonstration stage, focusing on power plants and especially on floating units where it may be additionally exploited the water body to avoid overheating of the panels. This is presented

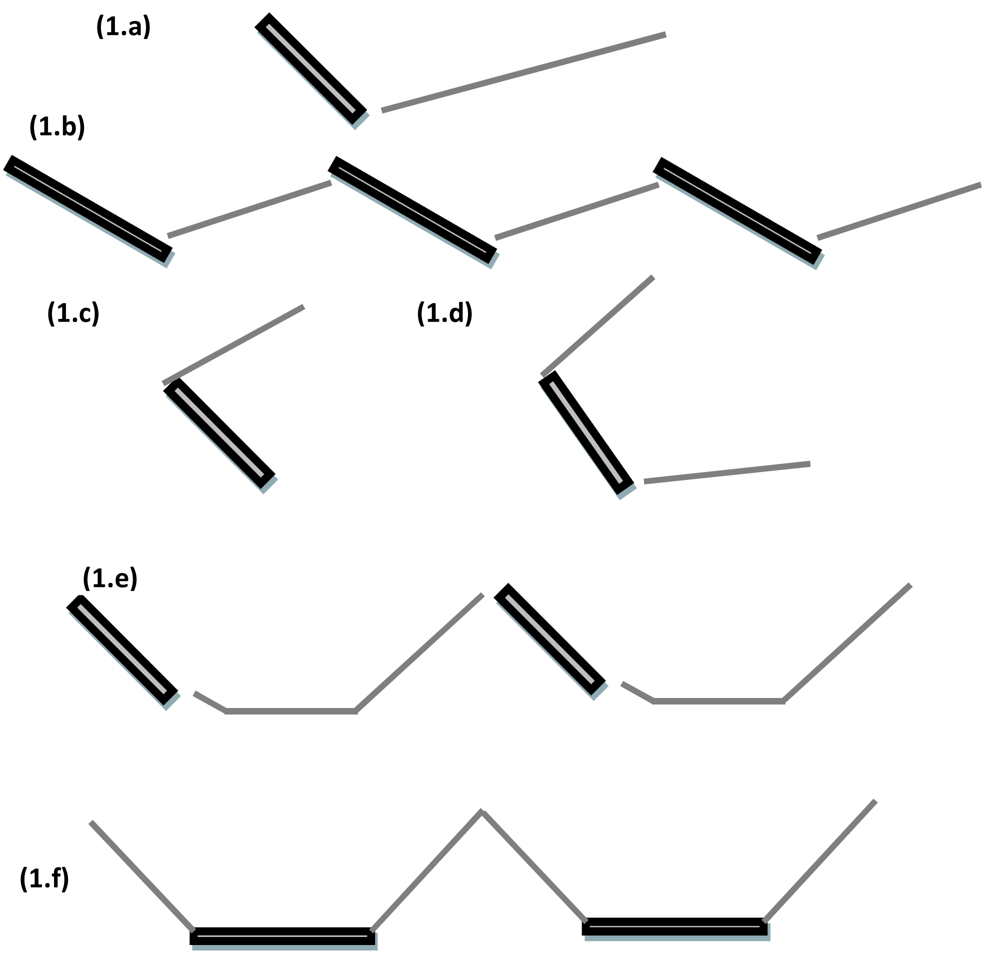


Figure 1. Various tested arrangements of flat booster reflectors with PVs. (a) Single unit, (b) Same as previous, but in arrays, (c) Reflector on top of the PV to protect it from snow, (d) With two reflectors at a single unit (trough arrangement), (e) With two reflectors in arrays (floating unit), the one mirror at horizontal position, (f) With two reflectors in arrays, (floating unit), the PV at horizontal position for cooling.

in details in [12], and the arrangements of the PV panel / reflector module used are similar to that of Fig. 1.b, 1.e or 1.f. In general the installed plants use either a single reflector with the PV panel placed at the optimum tilt angle (e.g. Floating Tracking Cooling Concentrator (FTCC) platform in Suvereto, Italy) or two reflectors with the panel being either inclined or at horizontal position, placed between two reflectors tilted at angles of 60 degrees (e.g. Scienza Industria Tecnologia's FTCC system in Colignola, on the outskirts of Pisa). Apart from these, there has been developed an application in Sweden, with the reflector placed on top of panel (see Fig. 1.c). This arrangement is used for street lighting, and simultaneously succeeds augmentation of solar radiation and protection of the panels against the snowfall [4]. Last, demonstration projects are also developed in other places worldwide, like in South Korea (FTCC system in Cheongju) etc. [13].

Despite the afore-mentioned successful experiments and applications, the use of flat booster reflectors is still limited and is not ordinarily considered as an option in photovoltaic projects. A reason may be the marginal economic benefits by adding booster reflectors, which is mainly due to the continuously decreasing of PV modules prices. Besides, the economy of such systems is site and application specific, rendering in this way difficult the transfer of experiences between projects. In this context, the technical and economic advantages of booster reflectors should be separately considered for each distinguished application and location, while any consequent side effects should not be ignored (e.g. cooling effect on roof installations, low irradiation and less algae growth in pond installations, substitution of imports etc.). Moreover, the several experimental results and commercial applications of reflectors to PVs seem to focus on the potential increase of the annual electrical yield, taking as granted that the PVs are placed at their optimum tilt angle. As a consequence there have not been considered cases where the PVs should be placed at quite different than the optimum tilt angle (e.g. vertical placement on facades) neither has been regarded the actual effect of the reflectors to the profile of the energy source, a factor which is critical in stand-alone applications. In the present work the distinguished techno-economic advantages of attaching booster reflectors to PVs for a variety of applications is investigated in the framework of case studies, using to this aim the climatic data of Athens, Greece.

2. Methodology

2.1. The Method

The main parameters that specify a PV/reflector module are (i) the slope β of the PV panel (ii) the inclination ζ of the reflector from the horizontal plane, and (iii) the reflector to PV width ratio *p*/*n* (see Fig. 2). When a diffuse reflector is used in front of a PV panel, the reflected radiation is proportional to the respective view factor $F_{R\text{-}PV}$ from the reflector (*R*) to the PV panel (*PV*). The plane angle ψ affects the factor $F_{R\text{-}PV}$, and in the case of long arrays (e.g. large-scale solar applications) the view factor is approximated by the relation [5]:

$$F_{R-PV} = \frac{n + p - \sqrt{n^2 + p^2 - 2 \cdot n \cdot p \cdot cos(\psi)}}{2 \cdot p} \quad (1)$$

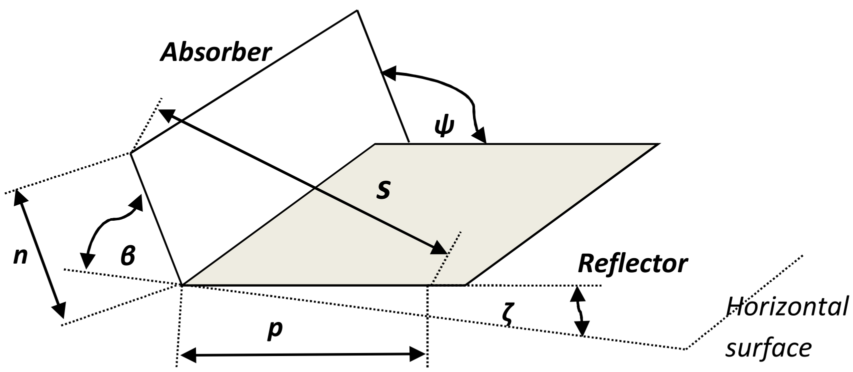


Figure 2. Design parameters of the examined PV/reflector arrangement

According to Eq. (1), the factor $F_{R\text{-}PV}$ decreases as the angle ψ exceeds 90^o and the vertical placement of the diffuse reflector to the panel is consequently the most advantageous. On the other hand, specular reflectance may result to greater concentration of solar radiation, leading in this way to higher increment of electrical yield. Indeed, during the comparison of reflectors made either of *Al-sheet* or alternatively of *Al-foil* (the latter has almost double specular reflectance, although both materials have approximately the same total - diffuse plus specular - reflectance), it was found the *Al-foil* reflectors to succeed almost 50% higher increase of irradiance in a typical summer day (August 12th), than that succeeded by using *Al-sheet* reflectors [6].

The effectiveness of booster reflectors is evaluated on the basis of the achieved increment on the PV panel annual electrical yield. In the case of specular reflectors, the optimum plane angle ψ is greater than the previously concluded value of 90^o for the diffuse reflectors and can be determined via optimization. Besides, the inclination of the whole module ζ (or equivalently the tilt angle β for the PV panel) should be additionally optimized. The greater the inclination ζ is, the higher the augmentation of incident irradiance achieved, although after an inclination value shading effects may become significant. Last, concentration of incident solar radiation increases with p/n ratio, but simultaneously does also increase the cost of the reflectors.

The increase of annual electrical yield can be estimated through the integration of the incident irradiance and the efficiency of the PV panel. Two types of PVs panels are assumed: (i) panels made of mono-crystalline silicon (*m-Si*) cells and (ii) panels made of amorphous silicon (*a-Si*) cells. Although the latter present the lowest conversion efficiency, they succeed the best use of the unevenly distributed radiation on them. When the cells are made of crystalline silicon, then the electrical yield is proportional to the evenly distributed illumination, and in this context the minimum value of illumination should be regarded in the calculations only. On the other hand, when a thin film panel is used instead, then almost the whole uneven irradiance is exploitable, and in this way the mean incident solar radiation should be considered in the estimation of the expected electrical yield.

Increase of irradiance leads to higher panel temperature and in this way to lower solar energy conversion efficiencies as well. As a consequence, the electrical power may not be proportional to the short circuit current or to the irradiance, with the deviation from the proportionality becoming greater at places with higher direct solar radiation and ambient temperatures. As a first approximation, the electrical power output of the PV module could be assumed proportional to the irradiance [3], provided either that efficient cooling of the module is simultaneously applied, or that solar energy augmentation is only effected early in the morning, late at noon and in winter time. For more accurate calculations however, the irradiance on the panel should be assessed in relation with the induced temperature increase caused by the solar radiation concentration, and then the efficiency of the panel be appropriately corrected, as it is applied in the present work.

2.2. The Model

A model was developed for the needs of this study, which uses as data the solar radiation and the ambient temperature of the site, in order to estimate:

i) the total irradiance on a panel equipped with a reflector
ii) the temperature of the panel, as this is affected by the increased irradiance, and finally
iii) the expected electrical output.

A time step of one hour was used for the simulation. The hourly solar radiation data were produced from monthly insolation data, according to methods proposed in [5]. The model, which is presented in details in the *Appendix*, was mainly based on previously published models [14,15] and was tested for its accuracy. To this aim, measurements of total irradiance on horizontal surface, of diffuse irradiance on horizontal surface, of irradiance on the tilted surface of the panel and last of total irradiance (including solar radiation from the reflector) were firstly executed for various angles. The estimations of the model compare well with the actual measurements, as it is shown in Fig. 3 (error less than 2%), proving the accuracy of the basic equations of the model (Eq. (A.1) to (A.11)).

Measurements were afterwards undertaken to test the behaviour of *m-Si* and *a-Si* panels in uneven illumination, in order to validate the respective part of the model (see Appendix, section A.2). In Fig. 4, measurements of the short circuit current (I_{sc}, as a relative value) are presented, when part of the panels are entirely shaded. It becomes

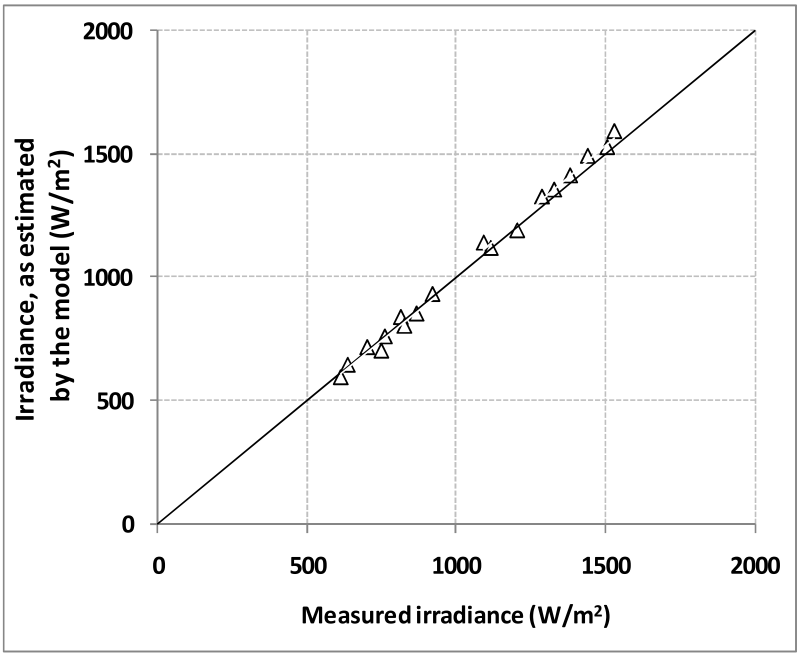


Figure 3. Correlation between actual measurements and model estimations

apparent that in *m-Si* panel the value of I_{sc} drops rapidly with shading, while in *a-Si* panel the I_{sc} decreases slowly, depending strongly on the direction of shading as this is related to the arrangements of the cells. Our measurements proved to be in agreement with previously published data [3], but also with the outcome of a more recent research [16] which focuses exactly on shading effects on amorphous silicon PVs. Results from this last research, regarding the impact of 60% shading on part of amorphous Silicon PV panel, are also shown in the same Fig. 4. The conclusions from both partial or complete shading is that the electrical yield of the *a-Si* panel is proportional to the unevenly incident radiation on the panel, provided that shading proceeds perpendicularly to the longer axis of the elongated cells (all cells are partly and equally shaded), as it is exactly described with equations (A.12) to (A.15) of the proposed model.

Last, the electrical output of the panel $E_{j,k}$ is estimated on hourly basis for the typical day of each month, according to the relation:

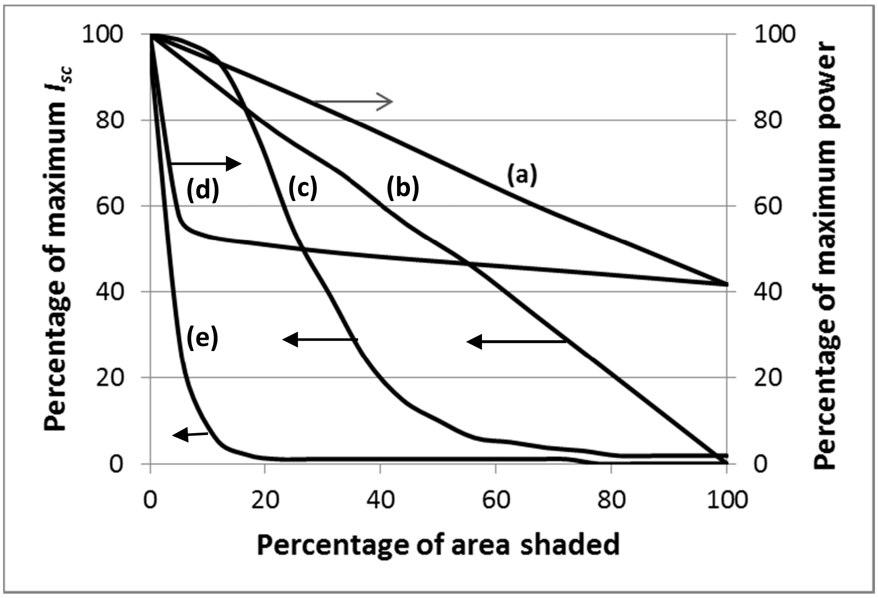


Figure 4. Effect of shading on mono-crystalline and amorphous silica PV panels. (a, b): Shading of a-Si vertically to the cells, (c, d):Shading of a-Si in parallel to the cells, (e): Shading of m-Si panel. Curves (a) and (d) refer to 60% shading, all other to complete shading

$$E_{j,k} = 3600 \cdot e_{PV} \cdot G_{j,k} \quad (2)$$

Here, j is the hour of the day, k the month of the year, and e_{PV} the efficiency of the PV panel appropriately corrected to take into consideration any overheating effect due to the temperature increase caused by the reflected radiation (as described in the Appendix, in section A.3). Finally, the expected annual electrical yield is obviously the sum of the above hourly estimates:

$$E = \sum_{k=1}^{12} N_k \cdot \sum_{j=1}^{24} E_{j,k} \quad (3)$$

with N_k being the number of days in each month.

2.3. Criterion for the Evaluation of PV/Reflector Modules

Two alternative criterions are generally used for the design and optimization of PV installations, namely the maximization of the energy produced or the maximization of the system net present value [17]. For a PV/reflector module however, the following criterions are additionally important: (i) the increase of electrical yield reduced per surface area (especially important for roof installations) (ii) the economy of the system, according either to the induced net earnings from the supplementary electrical yield or to the marginal production cost comparing the latter with the alternative addition of PV panels (important for land applications) (iii) the better matching of the deduced electrical yield with the profile of the load (important for stand-alone applications); all above are consequently considered in this work.

3. Applicability of PV/Reflector Modules in Buildings

Integration or simply attachment of photovoltaics in building (BIPV or BAPV, correspondingly) is a powerful measure to achieve the nearly zero energy targets. The respective prospects have been estimated for the EU-27 [18], by assuming the buildings stock and the possibilities to apply photovoltaics on roofs and south facing facades, and has been concluded that BIPV may play a significant role in electrification of these Countries, with a potential to cover even more than 30% of the expected demand in 2030 in a few of them (e.g. Denmark, Hungary, Malta). Solar radiation augmentation may further improve these prospects. The concentrating BIPV were reviewed in [19] with an emphasis on medium to high concentration systems (e.g. C>10x), while for the low concentration systems the V-trough arrangements was scrutinised, and concluded that the latter may be beneficial provided that commercial cells are used and cell heating is reduced. Both thin film and crystalline silicon cells are used in buildings, as reviewed in [20]. Although crystalline silicon seems to prevail in these applications for the time being (share 93.5%), the situation is expected to change in the future (e.g. the thin-film PVs is predicted to acquire 50% of this market in 2030), due the versatility of the latter and the expected improvement of their efficiencies from 60% of that of crystalline silicon to 80% in the same end year [18].

3.1. Assessment of PV Panel / Reflector Modules, for Roof İnstallation

The proposed model was applied for the data of Athens (Greece), regarding as the reference scenario a conventional PV panel placed at the optimum tilt angle of 31^o (annual irradiation at 31^o tilt angle reaches in Athens 6150 MJ/m^2-yr). The radiation data used are according to the data-bases incorporated in relevant national technical guidelines and are almost identical with those of the Classic PVGIS [21] data base (the values in Climate-SAF-PVGIS data-base are slightly higher).

The PV arrays are usually installed at a spacing to avoid any shading at noon of December 21st. At that date, solar altitude angle in Athens is 29^o, and for a PV panel tilted at 31^o due south it is easily proved that the spacing factor (distance between the rows per panel width) must be ~1.8 m/m. Indeed, the same design values (tilt angle 31^o and spacing factor 1.8) were also found for Athens when optimizing roof installation to maximize annually produced energy [17]. These values were also adopted here for the PV/reflector modules, while the reflectors were assumed to be extended from the lower end of the PV panel to the upper end of the next panel in front of it, as per Fig. 1.b, (reflector inclination $\zeta=29^o$). In this arrangement the reflector to PV widths are almost equal (p/n=1.06). The consequent effect of the reflectors, as indicated in Table 1, reveals that there is a notable increase in total incident radiation but the evenly distributed radiation is only slightly enhanced. Since crystalline silicon PV panels are more often applied on roofs, due to the usually limited available space, alternative wiring between the cells could be preferably considered in order to get benefit from the uneven radiation, too. From the same table it becomes also apparent that the overheating effect, due to solar radiation augmentation, is of minor importance (increase of electrical yield is slightly less than the increase of incident radiation), obviously due to the rather low concentration achieved.

<u>Edge effects</u>

It is not always possible in roof installations to extend the reflectors beyond the limits of the arrays, and consequently some loss is introduced due to edge effects. In a string the poorer cell drives the whole string and so when one cell is not accepting reflected irradiation, then there may be no benefit for the whole string.

Table 1. Estimated increase of irradiation and electrical yield, by the addition of flat booster reflectors in a typical PV roof arrangement

	Percentage of increase (%)	
	in irradiation	**in electrical yield**
Consideration of even illumination only	4.8	2.8
Consideration of uneven illumination, too	15.4	13.2

This happens for instance early in the morning and late at noon, when the eastern and western parts of (or entire) PV panels are not exposed to reflected radiation.

The fact that side (or parts of the) panels are not exposed to reflected radiation for some period of the day would not entirely affect the current from the whole string, provided that the inverter bypasses the less illuminated panels. This kind of control however still allows some electrical loss from the bypassed modules. Alternatively, application of parallel wiring and appropriate power optimizer, to treat each PV panel separately, is an effective solution but increases the cost and complexity of the installation.

The developed model was applied to investigate the edge effects, assuming that there is no extension of the reflectors beyond the PV panels. A typical PV panel was assumed, having dimensions of 1.6x1.0 m^2 and being composed of 60 crystalline silicon cells of 156x156mm^2. In Table 2, the relative annual insolation on a PV panel of a row of PV/reflector modules (relatively to the maximum value) is presented for even and uneven illumination. From this table becomes apparent that a single panel may accept as low as 90% of the insolation value calculated for an infinitely extending reflector. This fraction however increases and approaches unit when the reflector to PV ratio decreases, the number of modules increases. For instance, a short string of 5 modules will accept about 98% of the irradiation being evenly incident, when the reflectors are extended to avoid edge effects. Hence, the assumption of about 2% losses due to edge effects is quite reasonable.

Table 2. Relative annual insolation on a PV panel of a row of PV/reflector modules (relatively to the maximum value), for even and uneven illumination.

		Number of reflectors in both sides of the module		
		0	**1**	**2**
Reflector to PV width ratio	**1**	0.94 / 0.91*	0.98 / 0.97	0.99 / 0.98
	2	0.92 / 0.89	0.96 / 0.95	0.98 / 0.97
	3	0.92 / 0.89	0.94 / 0.93	0.97 / 0.96

* *Even/Uneven illumination*

<u>*Economic evaluation*</u>

The economic evaluation is based on the expected income increase:

$$\Delta Income_j = PV_{area} \cdot \Delta E \cdot (1-b)^{j-1} \cdot c_{el} \quad (4)$$

as compared to the additional cost of the reflectors:

$$\Delta Cost = PV_{area} \cdot \left(\frac{p}{n}\right) \cdot c_{REF} \quad (5)$$

Here b is the productivity loss due to the PV degradation and index $_j$ refers to the j^{th} year, c_{el} is the feed in tariff of photovoltaic electricity (Greece is a Country where grid parity has not been reached yet [22]), and c_{REF} the cost of the reflectors (see also nomenclature, at the end of the text). It is mathematically proved that the Internal Rate of Return on Investment (*IRR*) satisfies the equation:

$$\Delta Cost = \frac{\Delta Income_1}{(1-b)} \cdot PWF(n, i') \quad (6)$$

where *PWF* is the present worth factor to discount the cash flow:

$$PWF(m, i') = \frac{(1+i')^m - 1}{(1+i')^m \cdot i'} \quad (7)$$

Table 3. Data for the economic evaluation of PV/reflector module on roof installation.

PV efficiency (thin film)	8%
Reflector to PV width ratio	1.06
Estimated increase in electrical yield	13.2%
Losses due to edge effects	2%
Productivity loss (PL) due to the PV degradation	0.8%
Duration of the investment	25 years
Feed-in-tariff (FIT) currently applicable in Greece	0.125 €/kWh$_e$
Cost of reflectors	20 €/m^2

and *i’* is an appropriately modified *IRR*, due to the introduction of coefficient *b*:

$$i' = \frac{IRR + b}{1 - b} \quad (8)$$

As a consequence it is valid:

$$PWF(m, i') = \left(\frac{p}{n}\right) \cdot \frac{c_{REF} \cdot (1 - b)}{\Delta E \cdot c_{el}} \quad (9)$$

The last equation can be easily solved to find *PWF(m,i’)*, afterwards to find *i’* via a trial and error method, and finally to calculate *IRR*. Assuming, for instance, the data of Table 3, we estimate ΔE=(6150 MJ/m^2-yr)·(8%)·(13.2%)·(98%)=63.6 MJ/m^2-yr = 17.7kWh$_e$/m^2-yr, *PWF(25,i’)* =9.50, then *i’*=9.4% and last *IRR*=8.5%, which is satisfactory. Notably, Eq. (9) additionally reveals that for the same technical data, the economy of the reflectors improves with the ratio c_{el}/c_{REF}.

3.2. Installation of PV/Reflector Modules at Facades

PV panels may either placed on opaque facades (as BAPV) or as solar cell glazing products (as BIPV) with transparencies ranging from 16-41% (depending on the distance between the cells) and can be made either of amorphous or of crystalline silicon [20]. South facing facades are more suitable to this aim, accepting e.g. 30% more radiation than the east or west oriented vertically placed surfaces (according to the data of Athens).

Nevertheless, the installation of the panels in a vertical position, even at south orientation, is quite inferior to the optimum tilted placement (at 31^o) accepting almost 40% less solar radiation. The placement of horizontal reflectors in front of the vertical panels may counterbalance the losses caused by the increased tilt angle. Hence, it was calculated here that an equal area of reflectors is sufficient to increase the electrical yield to reach 90% of its value at the optimum tilt angle, which means almost 50% higher electrical yield and a pay-back period for the reflectors within 2.2 years only.

Special building materials could be also used to this aim, in the place of reflectors. In general, light building materials have a total reflectivity of 0.6 [23]. Polished materials however achieve higher specular reflectivity (total reflectivity remains practically unchanged, [24]). Hence, polished concrete floor, porcelain tiles, floors with reflective coating etc. may succeed reflectivity approaching 80%. For instance, high class polished concrete (e.g. Level 4, polished to more than 800 grit, [25]) may reach a gloss value of more than 0.75 [26], acquiring in this way a mirror like surface and an equivalently high specular reflectivity. Such an arrangement however may present side impacts, affecting the functionality of the surrounding the building area, and in this way it may be more appropriate for industrial buildings and warehouses.

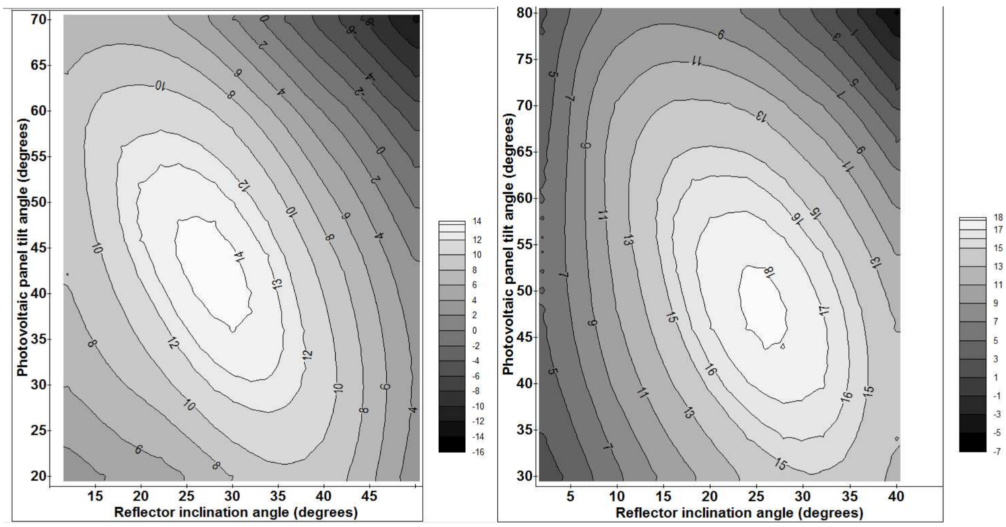
4. Applicability of PV Panel / Reflector Modules in Ground İnstallations

In ground installations it is assumed that there are no space limitations and that all parameters (namely *PV* tilt angle, reflector inclination angle and reflector to *PV* width ratio) are subject to optimization. Relevant results are demonstrated in the form of contour maps for *p/n*=1.0, 2.0 and 3.0, in Fig. 5.a to 5.c, respectively. From Fig. 5 becomes apparent that the optimum inclination angle for the reflectors is between 20-30^o, varying with *p/n* ratio but remaining quite close to the previously assumed value (29^o, see section 3.1). On the other hand, the optimum *PV* tilt angle varies in the range of 45-50° which is significantly higher than the previously assumed value (31°).

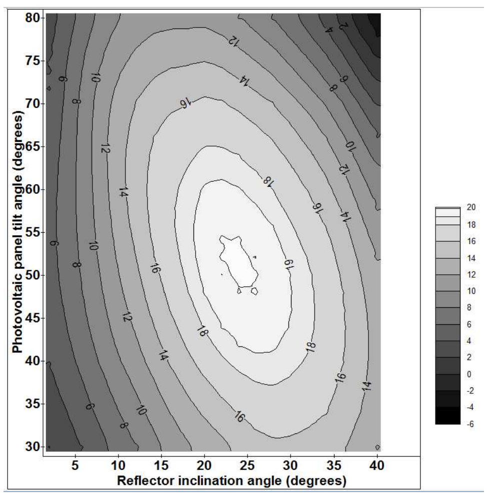
The variation of optimum values with *p/n* is shown in Fig. 6 together with the expected increase in electrical yield. The additional cost of the reflectors must now be compared to the cost of equivalent area of PV panels that would lead to the same supplementary electrical yield. It is easily proved that this cost ratio is:

$$\frac{Cost\ of\ reflectors}{Equivalent\ cost\ of\ PVs} = \frac{A_{PV} \cdot \left(\frac{p}{n}\right) \cdot c_{REF}}{A_{PV} \cdot \left\{\frac{E_{MOD}}{E_{PV}} - 1\right\} \cdot e_{PV} \cdot 1000 \cdot c_{PV}} = \left(\frac{p}{n}\right) \cdot \left(\frac{c_{REF}}{10 \cdot e_{PV} \cdot c_{PV}}\right) \cdot \frac{1}{(\Delta E\%)} \quad (10)$$

Hence the reflectors are economical as far as the above ratio remains less than unit. According to the assumed data, the variation of this ratio with *p/n* is presented again in Fig. 6. From Fig. 6 becomes apparent that the reflectors are advantageous until an area of *p/n*~1, but also that the resulted benefits are not so important, since the achieved increase in electrical yield is no more than 10% in the range of interest. Notably, Eq. (10) additionally reveals that for the same technical data, the economy of the reflectors improves with the ratio c_{PV}/c_{REF}.



(a) *(b)*



(c)

Figure 5. Effect of PV tilt angle and reflector inclination on electrical yield.
(a): p/n=1, (b): p/n=2, (c): p/n=3

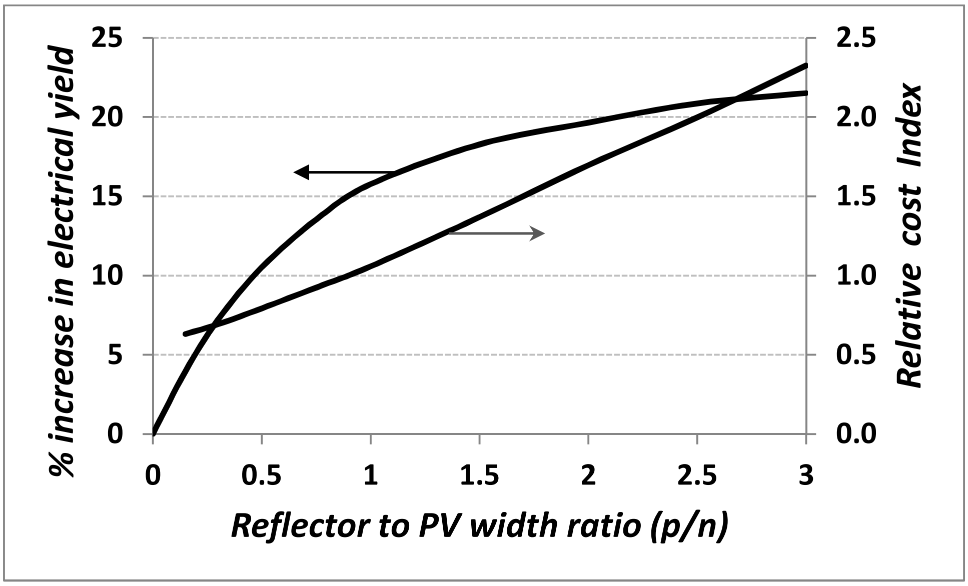


Figure 6. Effect of reflector to PV width ratio on the electrical yield and on the cost of the system

5. Applicability of PV/Reflector Modules in Stand-Alone Applications

Off-grid installations may serve the needs of a complete system (e.g. remote housing, refuge etc.) or of single applications (e.g. desalination, water pumping and irrigation, light-boy etc.). A matching between the size of the load and the production from the PV arrays is attempted through the appropriate sizing (PV area) and installation of the arrays (tilt angle). Shortage or surplus of electricity is managed through the convenient use of batteries and generators. Such an integrated autonomous system should be designed as a whole, e.g. minimizing total cost of PV panels and batteries, setting simultaneously an upper limit for the load not covered by the solar energy. A simpler approach is quite often applied [27,28], where the tilt angle of the panels is firstly specified depending on the period when peak loads occur (e.g. lower tilt angle for summer loads etc.), the area of the PV panels is afterwards determined, based on the solar radiation data of the month with the relatively –to the load- lower solar energy potential (normalised energy potential), and last the size of the batteries is calculated based on several technical considerations (days of autonomy, need for frequent levelling charge, allowable depth-of-discharge, adequate lifetime etc.).

This approach generally leads to over-dimensioning of the PV panel (and consequently to high capital costs) and greater surplus of electricity production, due to the generally mismatching between the annual variations of the energy source and of the load. Optimization of the tilt angle may improve matching but still the respective profiles could be quite different, as for instance may be the case of a roughly constant load all year around. The respective mismatching is in this case revealed by the expected electrical yield source annual variation, as it is demonstrated in Fig. 7 for various tilt angles. The application of reflectors in front of the panels introduces two more parameters for optimization (reflector inclination angle and reflector width) and in this way offers more degrees of freedom in the design of the system, allowing a better source/load matching with less impact on the productivity of the panels. This is shown in the same Fig. 7 where, by the use of reflectors, the monthly variation of electrical energy yield decreases approaching better the profile of the load. As an example, installation of PVs at the optimum tilt angle in Athens results to a standard deviation of the monthly electrical yield 30% of their mean monthly value. Alternatively, if the PV was vertically installed (β=90^o), and a double width reflector was placed horizontally in front of the panel (ζ=0^o, p/n=2.0), then almost the same quantity of electrical energy would be produced but more uniformly within the year, with the standard deviation being 13% of the mean monthly value. Actually, the normalised solar energy potential is increased in this way by 42% which consequently decreases the required capacity of the PV by 30%.

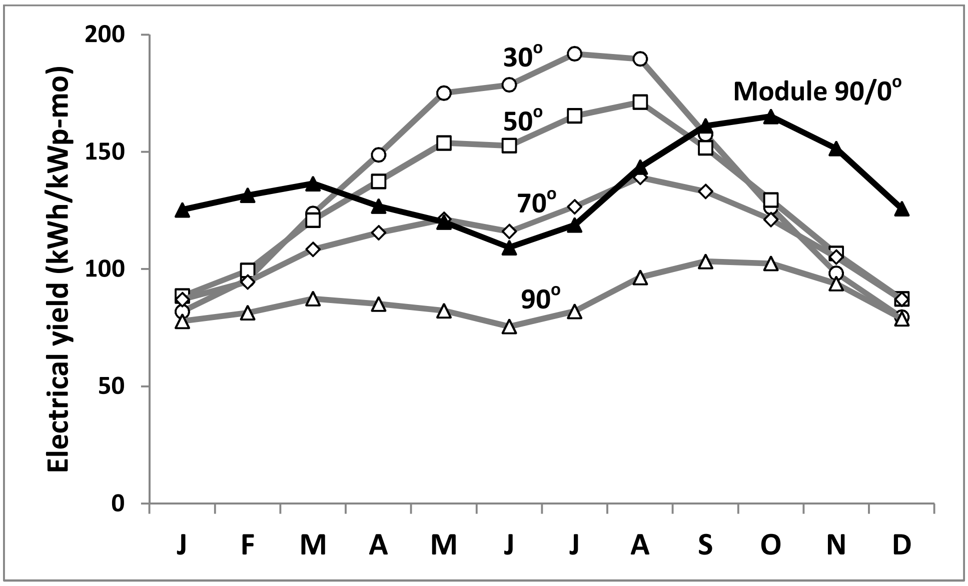


Figure 7. Expected electrical yield of PVs for various tilt angles (at 30^o, 50^o, 70^o and 90^o), as compared to the yield from a PV/reflector module (at β=90^o, ζ=0^o, p/n=2.0).

Integrated economic optimization is more complicated than the above simplified design approach, and a few methods have been proposed to this aim, based on semi-analytical models instead of a trial and error process [29,30]. These methods were reported in [31] and more recently in [32], while in the latter research an alternative approach based on stochastic time series for the solar energy data is proposed, to more accurately estimate the reliability index of the system. These integrated approaches revealed the interrelation between PV area and battery storage capacity, which is attributed to the daily variation of solar radiation within a month (statistically expressed by the standard deviation in the daily insolation for the month used to design the system). Nowadays detailed simulators are available to this aim, allowing the accurate optimization of complicated (e.g. hybrid) stand-alone systems (although the previously mentioned methods may still offer some benefits –due to their analytical basis-allowing a quick overview of the behaviour of the system). Actually, researchers are used to apply either a general purpose enginering simulator like MATLAB/Simulink (e.g. [33]), or a dedicated simulator like Hybrid Optimization Model for Electric Renewable (HOMER) is (e.g. [34]). In this context, we additionally investigated the economic effect of booster reflectors by using the specialized software package HOMER®. The same data were assumed again (solar radiation of Athens, Greece), while as energy source data for the PV/reflector module were introduced the estimations of the presently developed model for PV tilt angle 90^o, and reflector inclination angle 0^o, reflector to PV ratio *p/n*=2. A constant load was assumed, following a daily profile similar to that assumed in [30]. The acceptable annual capacity shortage was found to be critical in the alternative design of a PV/reflector system, as it is shown in Fig. 8. Specifically, the savings in PV panels increase with decreasing the above factor, allowing up to 25% savings in PV costs. At the same time however the cost of the system is charged with the cost of the reflectors, and in this context total cost savings are achievable provided that the reflectors are supplied at a cost lower than the assumed value of 20€/m^2, which is quite probable however. Indeed, taking into consideration that mirrors have become a principal building element, stimulating in this way their massive production and leading to FOB prices even lower than 2€/m^2, the above assumption for the reflectors price seems quite conservative.

6. Conclusions

Addition of booster flat reflectors in front of PV panels may remarkably increase the mean irradiance on the panel, especially for some hours around the solar noon, provided that appropriate PV and reflector inclination angles have been selected. Nevertheless, the use of the booster reflectors does not similarly improve the economy of the PV system. The reasons for this are: the uneven distribution of the reflected radiation on the surface of the panel, the edge effects at the end panels, the temperature increase of the cells due to the solar

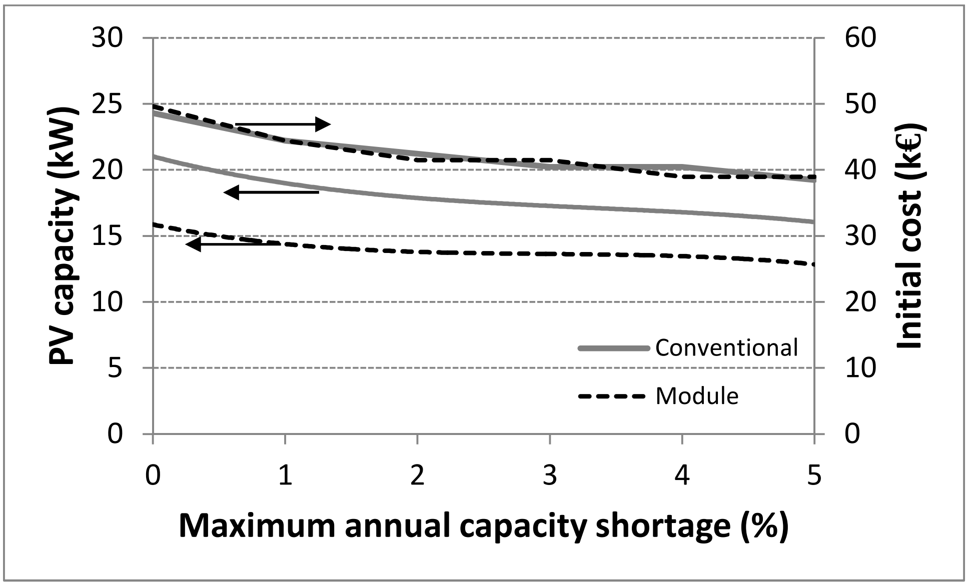


Figure 8. Required capacity of PV array for various acceptable values of annual capacity shortage, and respective initial cost of the system for 20€/m^2 assumed reflectors cost.

radiation concentration and last but not least the cost of the added reflectors.

Several alternative arrangements have already been tested to this aim in various places around the world, with quite encouraging results, while some of them have already been commercialized. The economy of these systems however depends on the design, on the local solar radiation data and, more importantly, on the prevailing economic parameters with most critical of them being the feed-in-tariff, the cost of the PV module and the cost of the reflectors.

For the city of Athens it was more specifically found that by placing reflectors between conventionally arranged PV strings on roofs, then the electrical yield may increase up to 13.2% leading to an IRR of the reflectors of 8.5%. For ground installations it was also found that reflectors may be competitive to the addition of more PV panels, when their width does not exceed the PV panel width (hence, up to a ratio p/n=1). Flat booster reflectors seem also advantageous for specific applications like for use with photovoltaics attached on buildings facades (leading to a pay-back period of less than 2.5 years), as well as in stand-alone applications where they allow the avoidance of PV array over-dimensioning; for the case study again, the reflectors are economical provided that they can be supplied at a cost less than 20€/m^2.

Acknowledgments

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Nomenclature

b	productivity loss due to the PV degradation
c_{el}	price of electricity (€/kWh)
c_{PV}	cost of PV panels (€/W)
c_{REF}	cost of reflectors (€/m^2)
e_o	*PV* module efficiency at reference temperature T_o
e_{PV}	*PV* module efficiency
E	electrical output from the PV module [J]
$F_{R\text{-}PV}$	view factor from the reflector, R, to the PV panel
G	irradiance [W/m^2]
m	life time [yr]
n	width of the absorber [m]
p	width of the reflector [m]
T_{AIR}	air temperature [^{o}C]
T_{CELL}	cell temperature [^{o}C]
T_o	reference temperature (=25^{o}C)
Greek symbols	
α_P	solar profile angle [^{o}]
α_s	solar altitude angle [^{o}]
β	slope of the tilted PV panel [^{o}]
β_P	temperature coefficient for PV efficiency [K^{-1}]
γ_s	solar azimuth angle [^{o}]
ζ	inclination angle of the reflector [^{o}]
θ	angle of incidence [^{o}]
θ_z	zenith angle [^{o}]
ρ	reflectivity of the reflector
ρ_G	reflectivity of the ground
ψ	angle between absorber and reflector planes [^{o}]
Indexes	
$_{diff}$	diffuse
$_{dir}$	direct (beam)

gr ground
hor horizontal surface
PV surface of PV panel
REF surface of Reflector
ref reflected
total total

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APPENDIX: Description of the model

A.1. Basic relations of the model

The irradiance on the PV panel is the sum of the solar radiation from the sky (beam and diffuse), from the ground (reflected) and from the reflector (specular and diffuse). The relation giving the irradiance on a tilted surface (e.g. on the PV, $G_{total\text{-}PV}$) is analysed in direct (beam, $G_{dir\text{-}PV}$), diffuse from the sky ($G_{diff\text{-}PV}$) and reflected from the ground ($G_{ref\text{-}gr\text{-}PV}$), which are correspondingly given by the following terms [5]:

$$G_{total-PV} = \left(G_{total-hor} - G_{diff-hor}\right)\cdot\frac{cos(\theta)}{cos(\theta_z)} + G_{diff-hor}\cdot\frac{1+cos(\beta)}{2} + \quad G_{total-hor}\cdot\rho_G \cdot\frac{1-cos(\beta)}{2} \qquad (A.1)$$

The placement of a reflector in front of the PV panel may affect both the diffuse and the ground reflected incident solar radiation. The first impact is ignored, due to the small inclination of the reflector, while the second is approximated by modifying appropriately the relevant term:

$$G_{ref-gr-PV} \approx G_{total-hor}\cdot\rho_G\cdot\left\{\frac{1-cos(\beta)}{2} - F_{PV-R}\right\} \qquad (A.2)$$

with $F_{PV\text{-}R} = F_{R\text{-}PV} \cdot (p/n)$. The basic equations concerning the reflected radiation were given in [14] referring, however, to the solar noon (identical solar and module azimuth angles). For any other case however the calculations become more complicated. For the general case, the angle of incidence of the reflected beam to the panel is estimated as follows. The solar altitude and azimuth angles are firstly calculated, as these are seen from the surface of the reflector (in Fig. A.1, surface *ACE* is horizontal, and surface *ABD* is that of the reflector. It is obviously valid that α_s = *FAE*, ζ = *BAC*, γ_s = *CAE*):

$$\alpha_1 = \alpha_s - atan\{tan(\zeta)\cdot cos(\gamma_s)\} \qquad (A.3)$$

$$\gamma_1 = atan\{cos(\zeta)\cdot tan(\gamma_s)\} \qquad (A.4)$$

The quantities m_1, m_2 and m_3 are afterwards calculated as follows:

$$m_1 = \sqrt{tan^2(\gamma_1) + \frac{1}{tan^2(\psi+\alpha_{p1})}} \qquad (A.5)$$

$$m_2 = \frac{cos(\alpha_{p1})}{sin(\psi+\alpha_{p1})} \qquad (A.6)$$

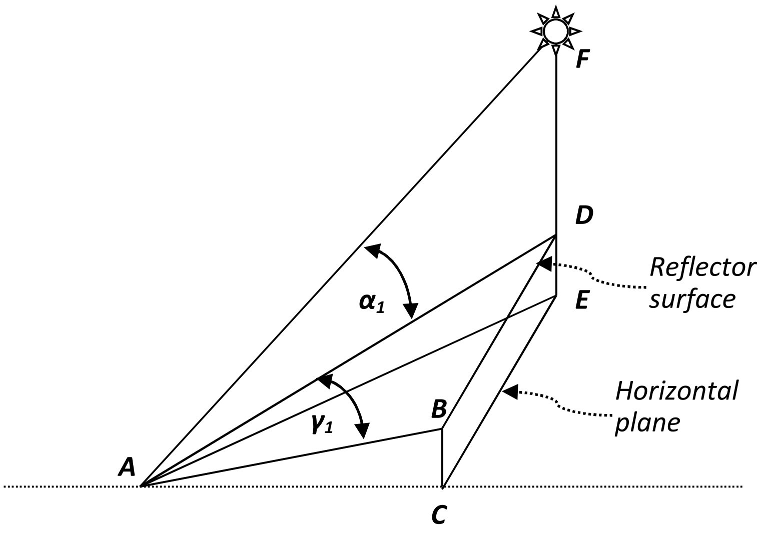

Figure A.1.

$$m_3 = \sqrt{tan^2(\gamma_1) + \frac{sin^2(\psi)}{sin^2(\psi + \alpha_{p1})}} \qquad (A.7)$$

where it is α_{p1} = (α_p – ζ) (see Fig. A.2) and α_p is the solar profile angle (the projection of the solar altitude angle to a surface vertical to the PV panel and the horizontal plane) which is given by the relation:

$$\alpha_p = atan\left\{\frac{tan(\alpha_s)}{cos(\gamma_s)}\right\} \qquad (A.8)$$

The angle of incidence θ’ of the reflected beam to the PV panel is finally calculated as:

$$\theta' = acos\left\{\frac{m_2^2 + m_3^2 - m_1^2}{2 \cdot m_2 \cdot m_3}\right\} \qquad (A.9)$$

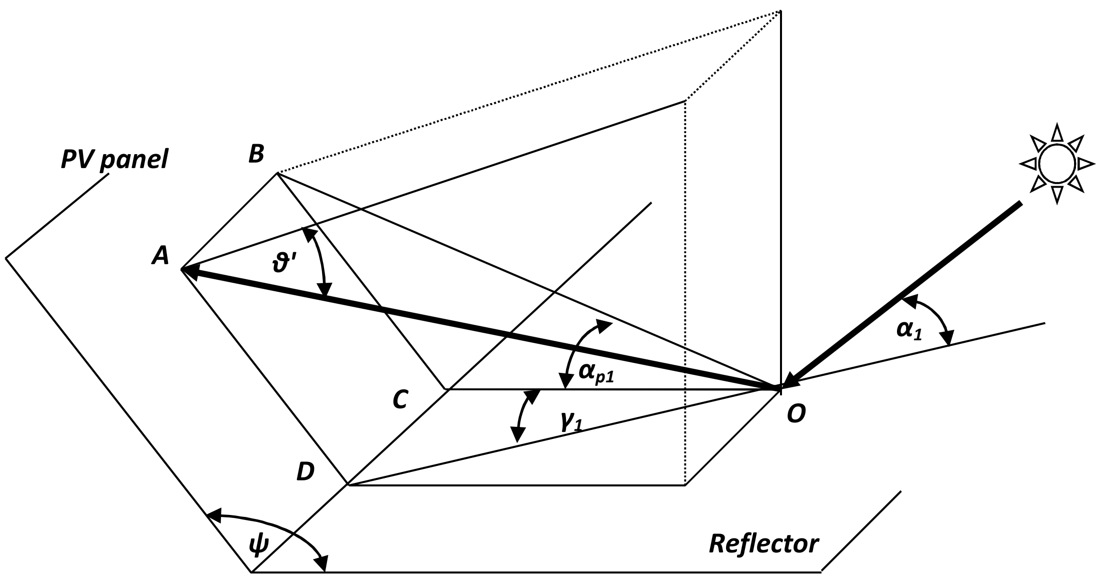

Figure A.2.

and the respective irradiance is:

$$G_{dir-REF-PV} = \rho \cdot G_{dir-hor} \cdot \frac{cos(\theta')}{cos(\theta_z)} \qquad (A.10)$$

with ρ to be the reflectivity of the reflector, $G_{dir-hor}$ the beam radiation on the horizontal plane and θ_z the zenith angle of the sun. This is the specular reflected radiation from the reflector to the PV panel (this additional radiation is taken into consideration in crystalline silicon panels only when the complete PV panel is evenly illuminated by the reflector, see section A.2).

Finally, the diffuse reflected solar radiation (although of minor importance) is also considered. This is due to the radiation coming from the sky (diffuse) and from the ground (reflected), which falls on the reflector and reflected as diffuse radiation. The part of this diffuse reflected radiation that reaches the PV panel is approximated by the relation:

$$G_{ref-diff-PV} \cong (1 - F_{R-PV}) \cdot \left\{ G_{diff-hor} \cdot \frac{1 + cos(\zeta)}{2} + G_{tot-hor} \cdot \rho_G \cdot \frac{1 - cos(\zeta)}{2} \right\} \cdot \rho \cdot F_{PV-R} \quad (A.11)$$

A.2. Limited extension of the reflectors - Edge effects

For some period of the day (in the morning and in the afternoon), top and side parts of the PV panel may not be illuminated by the reflector. The displacements *AB* (horizontal) and *AD* (on the tilted surface of the PV) of the trace of the reflected beam *OA* (Fig. A.3), when the last comes from the most remote point of the reflector, are respectively:

$$AB = p \cdot tan(\gamma_1) \qquad (A.12)$$

$$AD = p \cdot \frac{sin(\alpha_{P1})}{sin(\psi + \alpha_{p1})} \qquad (A.13)$$

For mono-Si PV panel, where the electrical output is proportional to the evenly incident radiation, the displacement on the tilted surface *AD* must at least exceed the width of the PV panel *n*, to get benefits from the incident reflected radiation (Fig. A.3). A similar restriction is valid for the horizontal displacement *AB*, which in the contrary must not exceed a minimum distance (e.g. the width of the cell when the length of the reflector is the same with that of the PV panel) or, alternatively, must not exceed the total length of the reflectors that precede the specific PV panel when numbered at the side where the solar beam comes from. Hence, the total irradiance which must be regarded for the estimation of the electrical output of a mono-Si PV panel $G'_{total-PV}$ is:

$$G'_{total-PV} = G_{total-PV} + G_{ref-diff-PV} + G_{dir-REF-PV} \qquad (A.14a)$$

when [$AD > EF$ and $AB < m \cdot EC$], otherwise:

$$G'_{total-PV} = G_{total-PV} + G_{ref-diff-PV} \qquad (A.15)$$

where *EC* is the length of each module and *m* is the number of reflectors (or modules) that precede the panel, counted as above explained.

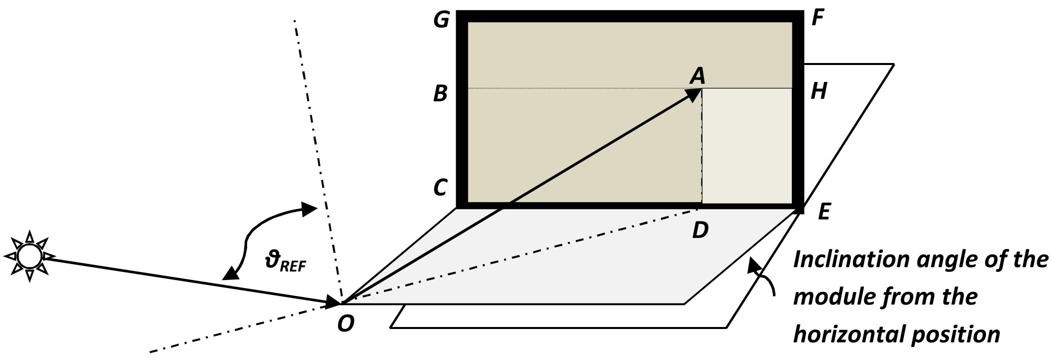

Figure A.3.

On the contrary, the condition *AD >EF* of Eq. (A.14a) is not necessary for the amorphous silicon PV panels. Actually, the electrical output is proportional to the mean incident radiation, and so the total irradiance that must be considered for the estimation of the electrical output of amorphous silicon PV panel $G'_{total-PV}$ is now:

$$G'_{total-PV} = G_{total-PV} + G_{ref-diff-PV} + G_{dir-REF-PV} \cdot \frac{(AD)}{(GC)} \qquad (A.14b)$$

when $AB < m \cdot EC$.

A.3. Effect of temperature

Increase of irradiance causes increase to the cell temperature T_{CELL} (^{o}C) according to the relation:

$$T_{CELL} = T_{AIR} + \frac{(NOCT - 25)}{800} \cdot G \qquad (A.16)$$

where T_{AIR} is the air temperature (^{o}C), *NOCT* is the normal operating cell temperature (^{o}C) and *G* is the irradiance on the panel (W/m^2). Increase of the cell temperature causes at the same time increase of current and decrease of voltage, the net effect of both above variations to be a slight decrease to the efficiency of the panel according to the relation:

$$e_{PV} = e_o \cdot [1 - \beta_P \cdot (T_{CELL} - T_o)] \qquad (A.17)$$

Here e_o is the *PV* module efficiency at reference temperature T_o (=25^{o}C) and β_P the temperature coefficient for module efficiency (a value of β_P=0.3% per Kelvin degree has been assumed in this work).