ON THE GEOMETRIC MODELLING OF A CONCENTRATING PV-MIRROR SYSTEM

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Abstract: *There are three main types of concentrating photovoltaic systems: low, medium and high concentrating ratio CPVs. This paper deals with a low concentrating system (with mirrors), its geometric modelling and working parameters. Through numerical simulations, the parameters' influences can be identified and thereby the path for optimization found. The aim is to maximize the received global radiation of the PV module, maintaining an overall geometric size of the system as small as possible. The additional received direct radiation, offered by mirrors, can lead to a significant increase in output energy.*

Key words: *low concentrating photovoltaic system, solar tracking, mirror angles, overall size.*

1. Introduction

Concentrating solar systems (CPV) use reflective and refractive optical devices to focus the solar light onto a photovoltaic surface and so to increase the power output. The aim of such a system is to reduce the expensive PV surface, but at the same time to increase the energetic efficiency by means of less costly optical materials and parts.

The most important aspect of this technology is the possibility to reach system efficiencies beyond 30% [3].

These solar energy systems are characterized by their concentration ratio (*CR*): low $CR < 10X$, medium $CR < 100X$ or high $CR > 100X$ [5].

Medium- and high-concentration systems require accurate tracking to maintain the focus of the light on the solar cells as the Sun is moving throughout the day. This adds extra costs and complexity to the system. The low concentrating ratio photovoltaic systems are of particular interest as they are of linear geometry and thus they do not require precise tracking. Compared with medium- and high-concentration systems, a low-concentration system can also convert the diffuse component of the solar radiation into energy, but only the direct component can be concentrated.

The medium- and high-concentration systems often use special optical devices to concentrate the light onto a PV cell of small dimensions. Many developers use special lenses as optical devices, such as Fresnel or Fly-eye lenses. An example of high-concentration CPV system is the one developed by Concentrix in association with Fraunhofer Institute Germany. The modules are called Flatcon [3] and are presented in Figure 1.

An example of medium-concentration CPV is the Spanish developer Zytech Solar [7], Figure 2, with a concentration ratio of 120X.

Low CPV systems are considered those that use standard PV technology in combination with simple optical devices (e.g. mirrors). Throughout the years, researchers and

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developers have brought on the market new solutions, some of which are presented below.

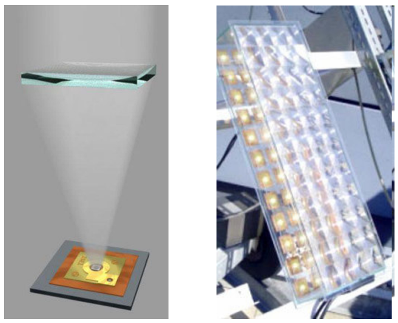
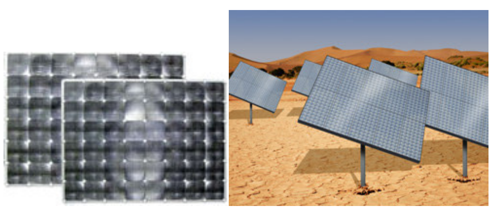


Fig. 1. *Left: The principle of PV concentration, using Fresnel lens optics; Right: CONCENTRIX compact concentrator systems using 2mm diameter multi-junction micro-cells operating at about 400* (*processed after* [3])

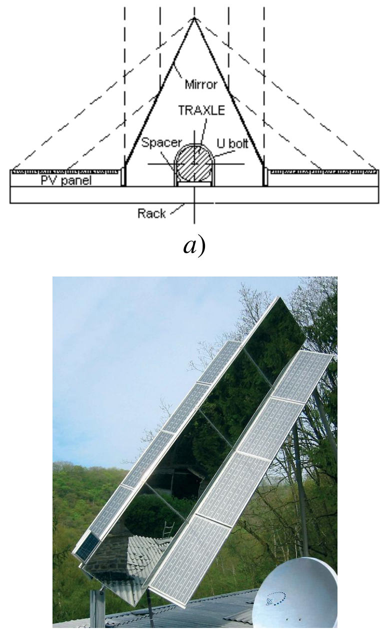


a) *b*)

Fig. 2. *a*) *Zytech Solar medium-concentration CPV module; b*) *Tracked Zytech Solar CPV system* (*processed after* [7])

The Czech company Poulek Solar has developed a line of tracked CPV: Traxel (see Figure 1). The concentration ratio is of 1.6 and the results show that on a bright day in July (6.8 kWh/m^2/day) the increase in the produced energy measured was by 107% [8].

Abengoa Solar [9] built the world's largest low concentrating PV plant (1 MW): Seville PV Plant. The Spanish plant has 154 two-axle tracking PV units, an example of which can be seen in Figure 4. Another developer, WS Energia [10], put on the market a simple independent low CPV system solution: Heliots (see Figure 3). The Portuguese company has reached an increase of 117% of the average energy produced by commercial modules.



b)

Fig. 3. *Traxel by Poulek Solar Co: a*) *Cross-section of the tracking concentrator; b*) *2 kW solar system* (*Luxembourg*) *with ridge concentrator* (*after* [8])

An American research team developed another simple and efficient solution, using standard PV technology and V-trough mirrors: Archimedes CPV system (see Figure 6) [4].

In this paper, a low-concentration system (similar to that shown in Figure 5) and its geometric modelling are presented, and the influences of its working parameters are further established. The research team aims to obtain a small overall size and the simplest tracking program that can ensure the highest solar radiation on the PV surface. Through geometric and numerical simulations, the parameters used for optimization are selected.

Fig. 4. *Abengoa Solar Sevilla PV Tracker* (*after* [9])

Fig. 5. *WS Heliots system, with DoubleSun technology* (*after* [10])

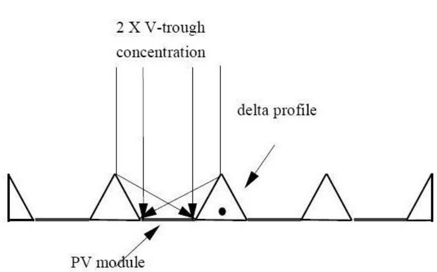


Fig. 6. *Archimedes Photovoltaic V-trough Concentrator System* (*after* [4])

2. Geometric Model of the Low CPV System

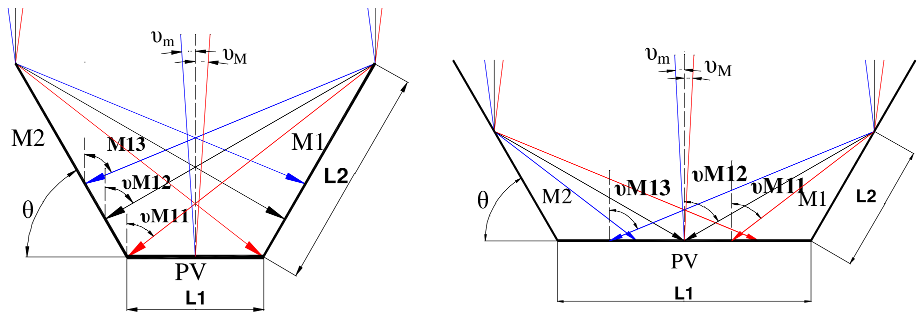
In order to determine the most adequate shape of the low concentrator system, geometric modelling was conducted.

The concentrator consists of a PV module and two mirrors, one on the left side and symmetrically on the right side along the length of the PV module. Based on the basic geometric model (Figure 7), two cases were discussed. In the first case, the solar radiation reflected from each mirror falls onto the whole surface of the PV module, assuring the double cover of the plane with reflected light (see Figure 7a). In the second case, the reflected light from each mirror falls onto half of the PV-module surface, building together one cover of light on the plane (Figure 7b).

In this paper, only the first case will be discussed, when the concentrated light from the mirrors covers all the surface of the PV-module (Figure 7a). Although this solution stands for the case when the system has the largest overall size, it also guarantees the greatest amount of solar radiation that falls onto the module, and thereby produces more energy.

The components of the system are: the PV module (PV), the right mirror (M1) and the left mirror (M2), symmetrically positioned.

The parameters of the system are: L - the length of the PV module and mirror; L1 - the width of the PV module; L2 - the width of the mirror; θ - the angle between the PV module plane and the mirror plane; υ - the current value of the incidence angle [1]; υ_M - the maximum incidence angle (when positioned to the right, $\upsilon_M > 0$); υ_m - the minimum incidence angle (when positioned to the left, $\upsilon_m < 0$); υM11, υM12, υM13 - the incidence angles reflected by the right mirror (M1) on the PV panel: right extreme, median and left extreme, respectively, and the corresponding υM21, υM22 and υM23 for the left mirror (M2).



a) *b*)

Fig. 7. *Low CPV models: a*) *when the Reflected Solar Ray from each mirror falls onto the whole surface of the PV module; b*) *when the Reflected Solar Ray from each mirror falls onto half of the PV module surface*

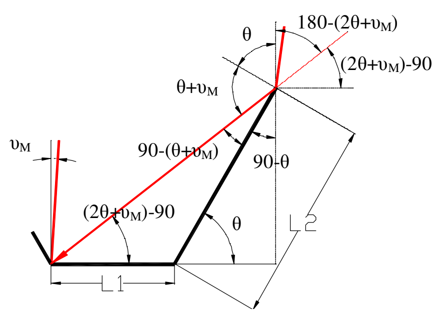


Fig. 8. *Geometric model used for the calculation of the ratio L1/L2*

In this paper, we considered υ = 15°, 7.5°, 3.75°, 1.875°, and 0.9375° corresponding to a time interval of 2 h, 1 h, 30 min, 15 min and 7.5 min, respectively, due to the fact that the Sun covers 15° in one hour.

The overall size depends on the dimensions L1 and L2 of the system. Knowing the width of a PV module (L1) we can determine the width of the mirror (L2), considering that the light is reflected on the whole surface of the module. According to Figure 8, we can write:

$$L1 \cdot \sin\left[(2\theta + \upsilon_M) - 90\right] = L2 \cdot \sin\left[90 - (\theta + \upsilon_M)\right], \quad (1)$$

$$\varepsilon = \frac{L2}{L1} = \frac{-\cos(2 \cdot \theta + \upsilon_M)}{\cos(\theta + \upsilon_M)}. \quad (1')$$

Based on expression (1'), the curve family presented in Figure 9 can be plotted, which shows that the width of the mirror increases with the tracking step duration, due to the inclination angle θ. For the next numerical model, the following values of θ are considered: 50°, 55°, 60° and 65°.

3. Influence Analysis of the Geometric Parameters by Numerical Simulations

Using such parameters as θ angle (50°, 55°, 60°, 65°) and tracking programs (tracking steps at: 2 h, 1 h, 30 min, 15 min), we can influence the overall size of the system and the received solar radiation. These influences can be observed in the diagrams below (see Figures 10 and 11).

The corresponding numerical simulations are conducted in the case of Braşov, Romania location (with latitude φ = 45.6 ºN), during the summer solstice (N = 172 and δ = + 23.5º).

The direct solar radiation is computed with the expression [6]:

$$R_D = R_0 \exp\left[-T_R/(0.9 + 9.4 \sin\alpha)\right], \quad (2)$$

$$R_0 = 1367[1 + 0.0334 \cdot \cos(0.9856\,N - -2.27], \quad (2')$$

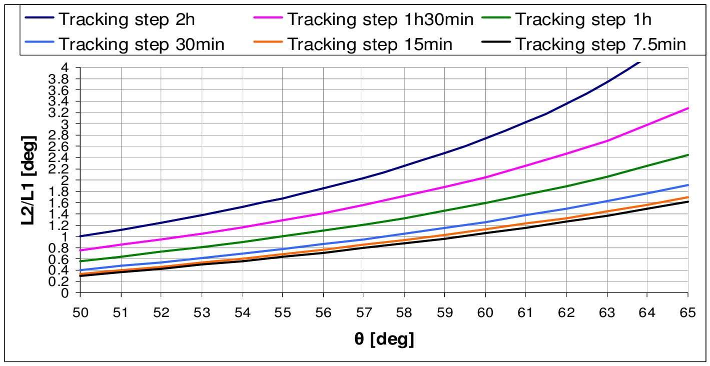


Fig. 9. *Variations of the ratio L2/L1 vs. mirror angle θ and tracking step duration*

where $T_R = 4.2$ is the turbidity factor [6], α is the altitude angle, and N is the day of the year.

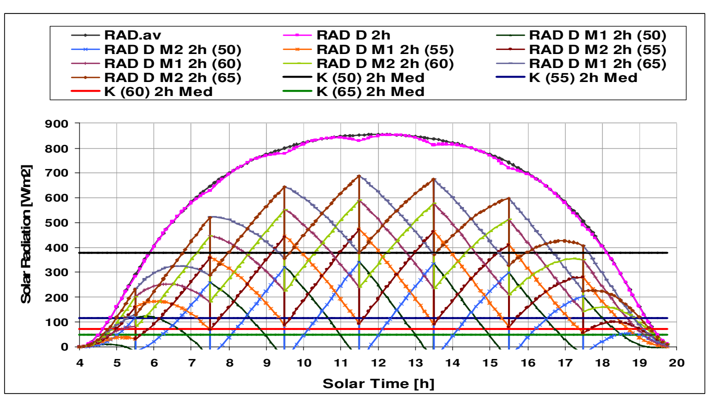
Starting from Figure 8, we can define the radiation power (K) normally received on the whole surface of the PV module through the reflection of light from one square meter of mirror (L1/L2) surface:

$$K = \frac{-Rd\cdot\cos(2\theta+\upsilon)\cdot L1\cdot L}{L2\cdot L}\ [W/m^2],\ (3)$$

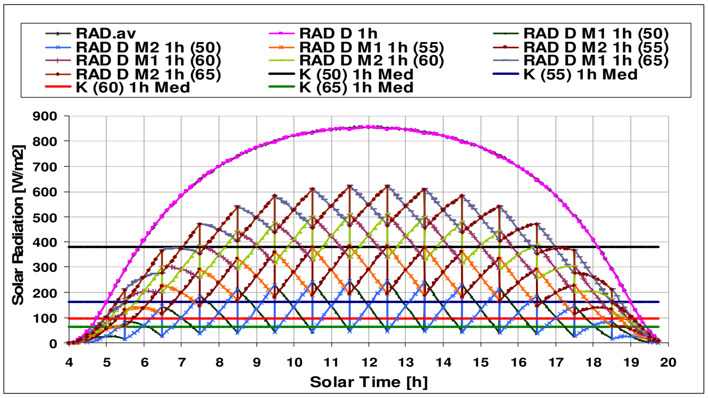
$$K_m = \frac{-\left[Rd\cdot\cos(2\theta+\upsilon)\right]_m}{\varepsilon}\ [Wh/m^2],\ (3')$$

where K is the instantaneous specific radiation on the dimension unit; L is the length of the mirror and PV module, and K_m is the average specific radiation on the dimension unit.

The diagrams in Figure 10 illustrate some variations in the direct solar radiation, at different tracking steps and θ values. In each diagram, the following elements are plotted: the available solar radiation, the radiation that falls onto the PV module, and radiations reflected from both mirrors. It can be observed that K_m is practically constant in all the cases presented, and one square meter of mirror has the same energetic participation on the PV module regardless of the orientation tracking program. The diagram in Figure 11 shows the total direct solar radiation that falls onto the PV module at two different tracking steps: 15 min and 2 h.



a)



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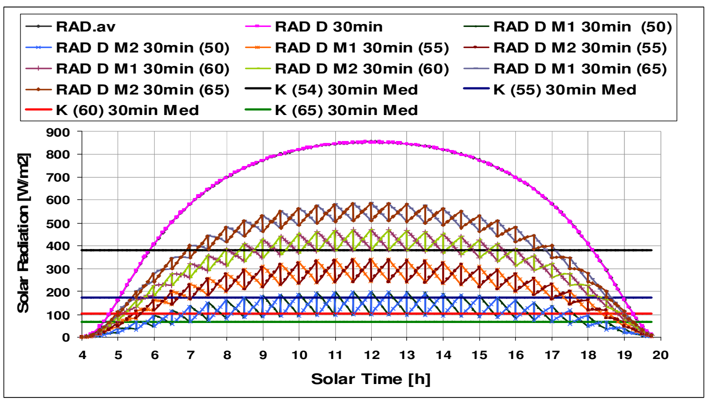
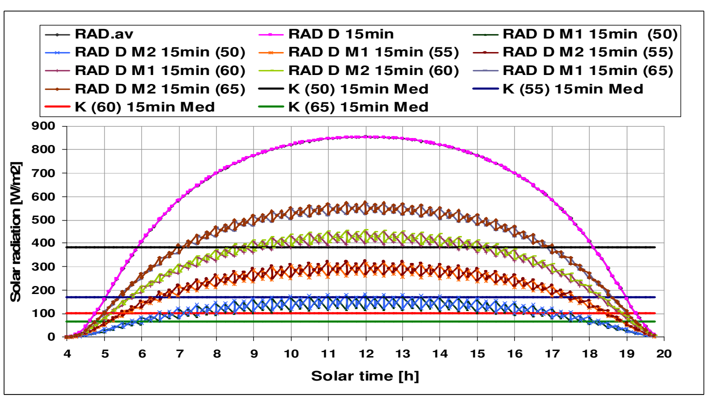


c)



d)

Fig. 10. *Variations in solar radiation from the mirrors at different angles, as compared with the available radiation at different tracking steps: a) 2 h; b) 1 h; c) 30 min; d) 15 min*

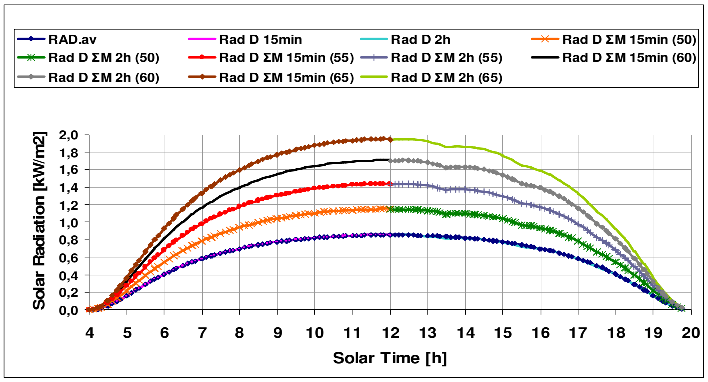


Fig. 11. *Total solar radiation that falls onto the PV module at different mirror angles and different tracking steps: 15 min and 2 h*

From the diagrams above, we can state that:

- the tracking step duration narrows down with the decrease of mirror width L1;
- the degree of non-uniformity of the direct radiation curve reflected from the mirrors onto the PV module increases with the tracking step duration (max = 2 h, and min = 15 min);
- the tracking step duration does not influence the average value of the radiation reflected from the mirrors onto the PV module;
- the systematized results in Figure 11 show that the total direct radiation received by the PV module does not depend on the duration of the tracking step, but on the value of θ (max. total radiation at θ = 65°, and min. at θ = 50°).

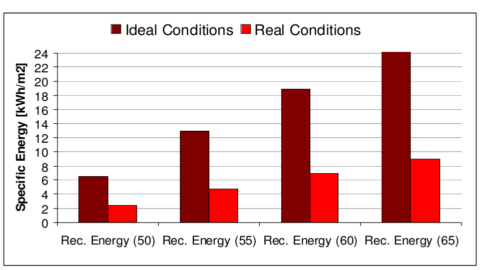


Fig. 12. *The direct solar energy received by the PV module, in ideal and real conditions, during the summer solstice in Braşov*

Under ideal conditions (e.g. clear sky), in Braşov area the energy received by the PV module is illustrated in Figure 12 by the column with the greatest value. The second column represents the energy received in real conditions; this value was obtained using the clouds crossing factor (*CCF* = 0.37 for 21st of June) [2]. *CCF* is the ratio of solar radiation under the clouds and solar radiation above the clouds [2].

The results of the simulation indicate a concentration ratio for the low CPV system of: *C* (50°) = 1.37, *C* (55°) = 1.68, *C* (60°) = 2 and *C* (65°) = 2.28.

4. Conclusions

1. There are three main types of solar PV concentrators: with high, medium and low concentration ratio. The low CPV system approached in this paper can work in two possible cases: a) when the reflected light from each mirror covers the whole PV module surface, and b) when only half of the surface is covered by light from each mirror. The case a) - analyzed in this paper - is modelled by means of the following parameters: L, L1, L2, θ, υ, υ_M, υ_m, υM11, υM12, υM13, υM21, υM22, υM23 (see Figures 7 and 8).

2. According to Figure 9, for the same

PV width L1, the mirror width L2 increases proportionally with the angle θ and the duration of the tracking program.

3. The mirror width decreases with the tracking step duration.

4. The tracking step duration does not influence the average values of the reflected radiation.

5. The total radiation depends on the angle θ, but not on the tracking step duration.

6. As a final conclusion, we can state that the concentration ratio increases with the increase of angle θ, so that a great value for *C* means a large overall size of the system.

References

1. Diaconescu, D., et al.: *The Incidence Angles of the Trackers Used for the PV Panels' Orientation. Part I: Equatorial Trackers*. In: ICEEMS - International Conference on Economic Engineering and Manufacturing Systems, Jurnalul RECENT, Vol. 8, nr. 3a (21a), Braşov, Romania, October 2007, p. 281-286.
2. Diaconescu, D., et al.: *Clouds Influence on the Solar Radiation for a Mountain Location.* In: Proceedings of the BRAMAT Conference, Braşov, 2009, p. 7-28.
3. Fraunhofer, I.S.E.: *Report EU Photovoltaic Technology Platform - The Strategic Research Agenda.* Working Group3 "Science, Technology and Applications; Activity: CPV, October 2006, Report by: Dr. A. Bett et al., p. 11-12.
4. Klotz, F.H.: *European Photovoltaic V-Trough Concentrator System with Gravitational Tracking.* In: Proceedings of the 16th European Photovoltaic Solar Energy Conference, Glasgow, UK, May 2000, p. 2229-2233.
5. Luque, A.L., Andreev, V.M.: *Concentrator Photovoltaics.* Berlin Heidelberg. Springer-Verlag, 2007.
6. Meliss, M.: *Regenerative Energie-quellen Praktikum.* Berlin Heidelberg. Springer, 1997.
7. www.zytech.es. Accessed: 18-02-2009.
8. www.solar-trackers.com. Accessed: 18-02-2009.
9. www.abengoa.es. Accessed: 18-02-2009.
10. www.ws-energia.com. Accessed: 18-02-2009.