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D. Chemisanadaniel.chemisana@macs.udl.catY. TripanagnostopoulosChr. LamnatouM. SouliotisJ. I. Rosell and J. Barrau

Citation: AIP Conference Proceedings **1477**, 217 (2012); doi: 10.1063/1.4753872
View online: http://dx.doi.org/10.1063/1.4753872
View Table of Contents: http://aip.scitation.org/toc/apc/1477/1
Published by the American Institute of Physics

Tilt Optimization Of A Building Integrated Solar Concentrating Unit

D. Chemisana[1,*], Y. Tripanagnostopoulos[2], Chr. Lamnatou[1], M. Souliotis[2], J.I. Rosell[1], J. Barrau[1]

[1,*]*University of Lleida, 25001 Lleida, Spain. E-mail: daniel.chemisana@macs.udl.cat*
[2]*University of Patras, 26504, Patras, Greece.*

Abstract. The concept of a static linear Fresnel concentrator with a tracking absorber has been simulated and well understood in the past. This paper bridges the gap between theoretical optical performances and operation in outdoor conditions. The effort focuses on the characterization of weather and tilt angle effects on the solar concentrator annual performance. Useful mathematical expressions are derived to show the dependence of the annual concentrated energy on latitude, global radiation, mean clearness index and tilt angle. An equation for the optimization of the annual yield is also proposed. The results are applied to a PVT generator and the annual production of thermal and electrical output energy is evaluated for an installation in Barcelona (Spain). A performance improvement above 5% is reached when the optimized tilt angle is used.

Keywords: Building integration, Fresnel, solar concentration, energy balance, nonimaging / anidolic.
PACS: 88.40fc, 88.40fr, 88.40mr

INTRODUCTION

Building Integration Of Concentrating Systems

At present, the use of Solar Concentrator systems is mostly limited to large installations with devices of considerable size and anaesthetic appearance from an architectural point of view.

Generalizing the criteria formulated by the IEA PVPS Task 7 workgroup to evaluate the aesthetic quality of well-integrated PV systems in buildings, and assuming that the characteristics of the integrating element are adequate from a constructive and technical point of view, solar concentrators that are to be integrated architecturally should fulfil the following requirements [1]: Natural integration, designs that are architecturally pleasing, good composition of colours and materials, dimensions that fit the gridula, harmony, composition, concentrating systems that match the context of the building, well-engineered design, use of innovative design.

Low concentrating ratio systems (C < 10X) are of particular interest since they are of linear geometry and thus one tracking axis is sufficient for efficient operation [2]. Furthermore, concentrating photovoltaics is a feasible method to reduce the high initial cost of photovoltaic solar energy. Concentrating the solar radiation onto solar cells implies that the area of semiconductor devices is diminished by replacing part of it with a cheaper element (the concentrator). Considering that a higher concentration factor results in higher cost reduction, it can be seen that within the concentration range where single axis tracking may be used, the most desirable concentration factor is that which approaches the upper limit of 10X.

Performance In Outdoor Conditions

To satisfy building integration requirements the use of a stationary Fresnel lens can be adopted. The application of linear Fresnel lenses in the design of a static concentrator with a tracking absorber was proposed some time ago [3]. More recently the first three-dimensional optical analysis of fixed Fresnel lenses has appeared, combined with a moving compound parabolic concentrator (CPC) receiver. Numerical results were obtained by geometric ray tracing to simulate the Fresnel lens behaviour under ideal illumination conditions [4]. OptiCAD®, a commercial computer program for ray tracing, was used to simulate the flux profile at the focus. The sun source was modelled in OptiCAD as a 'pillbox' shape, with half-angle set to 4.65 mrad. The beam ray was projected onto two planes, both normal to the Fresnel lens, which are parallel and perpendicular to the lens axis. The angles defined between the normal direction to the lens and the parallel and perpendicular projections of the beam ray are named the longitudinal (ψ) and transverse (θ) incidence angles, respectively. The centre of the focal area and the concentration ratio were evaluated for a wide range of incidence angles (ψ, θ). The ranges of incidence angles simulated were: $-70º < \psi < 70º$ and $-25º < \theta < 25º$. A polynomial expression for the concentration ratio as a function of incidence angles was fitted to the data obtained:

8th International Conference on Concentrating Photovoltaic Systems
AIP Conf. Proc. 1477, 217-220 (2012); doi: 10.1063/1.4753872

TABLE 1. Dependence of concentration ratio on solar incidence angles

Function	Coefficients	r^2
$(D0)+(D1)\theta+(D2)\theta^2+$	D0 = 9.317469 D1 = -2.47433851.10-16	0.96
$(D3)\theta^3+(D4)\theta^4+(D5)\psi+$	D2 = 8.20810458.10-4 D3 = 3.65912705.10-19	
$(D6)\psi^2+(D7)\psi^3+$	D4 = 8.03536735.10-7 D5 = 3.56808767.10-17	
$(D8)\psi^4+(D9)\theta\psi+$	D6 = 7.66543562.10-4 D7 = -9.75143971.10-21	
$(D10)\theta\psi^2+(D11)\theta\psi^3+$	D8 = -3.06797989.10-7D9 = 6.17840586.10-33	
$(D12)\theta2\psi^2+(D13)\theta^2\psi^2+$	D10 = 7.53207971.10-20 D11 = -2.63445299.10-36	
$(D14)\theta^2\psi^3+(D15)\theta^3\psi^1+$	D12 = -5.40022972.10-20 D13 = .17597364.10-6	
$(D16)\theta^3\psi^2+(D17)\theta^3\psi^3$	D14 = 1.46653710.10-23 D15 = 1.05759060.10-35	
	D16 = .12087636.10-22 D17 = +4.86285080.10-39	

The influence of the design parameters which affect to a large degree the aptitude of static Fresnel lens concentrators for architectural integration has been studied [5]. It was concluded that there is a dichotomy between compactness and optical concentration, one having to be given priority over the other depending on the desired requirements. In a system designed for level compromise between compactness and concentration, the design characteristics considered optimum are a dimensionless radius of curvature between 0.66 and 1.05 (which implies compactness between 1.25 and 1.75). Specifically, for a lens with a dimensionless radius of curvature of 0.77, the maximum geometric concentration is 12.5 suns.

In papers [4] and [5] deep numerical evaluations of the optical system where made for Fresnel lenses with the main axis oriented E-W and a standard solar incident flux profile. Simulated optical results were encouraging but the study did not address energy performance in outdoor building installations. The present paper introduces the influence of atmospheric and meteorological effects on the static Fresnel concentrator performance and describes how the Fresnel lenses perform when these effects are combined with different tilt angles.

The end results of the analysis are useful mathematical expressions to be applied by building engineers firstly to evaluate the energy performance of the system depending on location parameters, Eqs. (1,2), and secondly to determine the optimum tilt angle of the static concentrator, Eq. (4).

Performance Dependence On Key Parameters

Building integration of a solar concentrator based on a static linear Fresnel lens and a moving absorber offers aesthetically interesting possibilities. The size of the Fresnel lens can be adapted without modifying the basic design parameters (radius of curvature, geometric concentration ratio), but, due to the Sun´s movement and the acceptance angles of the optical system, not all the possible configurations are desirable considering the annual performance of the solar generator. Even for an E-W axis oriented concentrator some tilt angles should not be used. An example could be the use of standard photovoltaic modules in vertical façade installations which reach some production in middle latitude locations but are completely inefficient. Therefore, the design optimum tilt angle and its location parameters dependence should be evaluated.

Dependence On Location Parameters

Concentration ratio values obtained from the function defined in Table 1 are far from uniform, achieving and average value of 8.3X with a deviation of 63%. The ratio results from the interaction of the beam solar radiation annual distribution and the optical concentrator performance. Therefore, for engineering applications the solar energy concentrated in outdoor conditions should be explicitly expressed as a function of easily determined parameters.

To evaluate these key parameters the software Trnsys® 16 has been used. The optical performance of the Fresnel concentrator has been included as a new Trnsys type. The evaluation of the performance of the concentrator has been conducted for very different climates, based on weather data sets for the following locations: Graz, Beijing, Helsinki, Paris, Freiburg, London, Athens, New Delhi, Baghdad, Tehran, Rome, Sapporo, Warsaw, Moscow, Barcelona, Almería, Stockholm, Bangkok, Tunis and Harare.

The linear concentrator is E-W axis oriented and the tilt angle selected for the static Fresnel lens is equal to the latitude. On detailed analysis of different simulation sets the key parameters are determined to be: latitude L (º), annual global radiation in the horizontal plane G (kWh/m2) and mean monthly clearness index Kt (dimensionless). The clearness index is defined as the ratio of surface solar radiation to the extraterrestrial radiation for the studied period [6]. The following empirical expression for the annual solar energy received in the focal area of the Fresnel concentrator E (kWh/m2) as a function of the above parameters has been fitted to the numerical data.

$$E = a_0 + a_1K_t + a_2K_t^2 + a_3L + a_4L^2 + a_5G + a_6G^2 + a_7K_tL + a_8K_tG + a_9LG \quad (1)$$

Using the coefficients (a_i) listed in Table 2 a high R-squared value of 0.9977 is achieved.

TABLE 2. Coefficients involved in Eq. (1) and Eq. (2).

a_0	9.339808E+02	b_0	5.220208E+02
a_1	2.749850E+04	b_1	-2.686477E+00
a_2	2.223475E+04	b_2	-7.314082E-01
a_3	-8.511707E+01	b_3	2.328647E+04
a_4	8.871035E-01	b_4	7.347355E+03
a_5	-8.304031E+00	b_5	-5.705776E+01
a_6	4.452576E-03	b_6	1.625790E-01
a_7	-3.871725E+02	b_7	-6.880888E+00
a_8	-2.160935E+01	b_8	2.991523E-03
a_9	1.462040E-01	b_9	4.988601E+01
		b_{10}	1.154146E+00
		b_{11}	3.395350E-05
		b_{12}	-3.225071E+02
		b_{13}	-1.229438E+01
		b_{14}	1.057548E-01

Dependence On Tilt Angle

Due to building integration constraints the tilt angle may vary from the latitude angle. An extended version of Eq. (1) in which the tilt angle is included is therefore needed. Following a similar methodology to the previous section, Trnsys® simulations were performed for a range of locations and tilt angles, and the data set obtained approximated to the following equation:

$$E_c = b_0 + b_1 I + b_2 I^2 + b_3 K_t + b_4 K_t^2 + b_5 L + b_6 L^2 + b_7 G + b_8 G^2 + b_9 I K_t + b_{10} I L + b_{11} I G + b_{12} K_t L + b_{13} K_t G + b_{14} L G \quad (2)$$

The coefficients (b_i) shown in Table 2 give a high R-squared value of 0.9722.

Optimum Tilt Angle

In some building designs it may be possible to propose several global locations for the solar concentrator. In this case the designer can choose the optimum tilt angle generator according to the location characteristics. Maximising the total solar energy received in Eq (2) gives:

$$\frac{\partial E_c}{\partial I} = -2.686477 - 1.462816\, I + 49.886\, K_t + 1.154146\, L + 3.3953\times10^{-5}\, G = 0 \quad (3)$$

Yielding to the optimum tilt angle (I_{opt}) as a function of latitude, global solar radiation and clearness index:

$$I_{opt} = -1.836510 + 34.10271\, K_t + 0.788989\, L + 2.321098\times10^{-5}\, G \quad (4)$$

APPLICATION TO A BUILDING INTEGRATED PVT COLLECTOR

The aim of this section is to analyse quantitatively the gain in annual yield achieved by placing the system at the optimum tilt angle. The chosen receiver is a hybrid photovoltaic/thermal (PVT) generator; both electrical and thermal energy productions are quantified. The system is investigated under the weather conditions of Barcelona, Spain.

The concept of combining photovoltaic and solar thermal collectors to provide electrical and heat energy is an area that has, until recently, received limited attention. Although PVTs are not as prevalent as solar thermal systems, the integration of photovoltaic and solar thermal collectors into the walls or roofing structure of a building could provide greater opportunity for the use of renewable solar energy technologies.

The PVT receptor proposed here is not a commercial model and is described in detail in [7]. It is composed of photovoltaic cells (10 mm width) on top of an aluminium heat sink of rectangular cross section. Other essential elements of the module are: (a) An EVA film which is applied to the cells, and low reflectivity glass with low iron content is used as an outer shell; (b) The cells are attached to the heat sink, the adhesive used is a material with high heat transfer conductivity that is also resistant to extreme temperatures and is an excellent electrical insulator and (c) The lateral and underneath faces of the heat sink are thermally insulated. It is important to reemphasize that the PVT receptor is the sun tracking element.

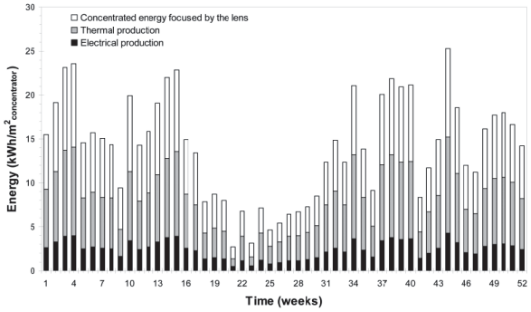
The PV cells reach a maximum electrical efficiency of 19.3%. The temperature dependence of the cell efficiency has been approximated by the following equation:

$$\eta_c(T_c) = \eta_c(25^{\circ} C)[1 - \beta(T_c - 25^{\circ} C)] \quad (5)$$

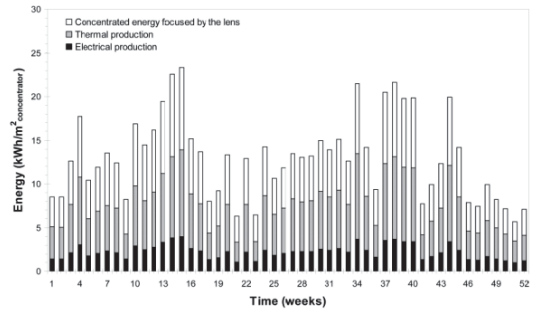
Where β for monocrystalline silicon is equal to 0.004 ºC^{-1}, η_e is the electrical efficiency of the PV cells and T_c is the average temperature of the solar cells.

The resulting optimal tilt angle position of the system for the case of Barcelona, is calculated directly by substituting into Eq. (4) the corresponding annual values of global radiation on the horizontal plane, clearness index and latitude, which are: 1531.90 kWh/m$^2_{concentrator}$, 0.5035 and 41.38º, respectively. The optimum tilt angle is found to be 48.02º. Since the optimum tilt angle is the inclination which maximizes the objective function: the energy concentrated by the lens, a comparison that illustrates this improvement is the representation of both the energy produced by the PVT generator when the concentrator lies at a standard inclination (tilt angle equal to the latitude) and the energy production calculated for the optimal angle.

The behaviour of the PVT module is more clearly understood when a weekly timescale is used. When the results are aggregated per month different effects are compensated for and hidden.



FIGUE 1. Module energy input and outputs (Tilt angle equal to the local latitude).



FIGUE 2. Module energy input and outputs (Optimized tilt angle)

In Figure 1 the electrical energy production, thermal energy production and direct concentrated radiation received, when the system is tilted in an angle equal to the latitude, are shown. The annual generations of thermal energy and electricity per unit concentrator aperture area (m^2) are 412.03 kWh/m^2 and 127.48 kWh/m^2, respectively. The global energy production is therefore 539.51 kWh/m^2. Regarding concentrator optical efficiency, it is necessary to underline that only direct beam radiation is focused on the receptor. The annual direct radiation in Barcelona is 1070.36 kWh/m^2 referred to the concentrator plane.

By tilting the concentrator to 48.02º, the energy production of the collector increases until reaching energy values per unit concentrator aperture area of 437.72 kWh/m^2 in thermal energy production and 136.79 kWh/m^2 in electrical production. Adding both values the overall energy production gives a value of 574.51kWh/m^2 (Fig. 2). On comparing with the results shown in the previous paragraph, it can be observed that the production has increased by 35.00 kWh/m^2, which represents a considerable improvement of 6.1%.

CONCLUSIONS

The studied concept is based on a stationary, wide angle optical concentrator which, whatever the location of the sun, transmits the input radiation onto a small moving focal area which is tracked by the receiver. The work focuses on the characterization of the effects of different weather conditions and tilt angles on the static Fresnel concentrator performance. From TRNSYS simulations of the optical device the useful mathematical Eqs. (1) and (2) are derived to show the dependence of annual concentrated energy on latitude, global radiation, mean clearness index and tilt angle. When building designs allow choice of concentrator tilt, the designers can use the proposed Eq. (4) to optimize the annual yield.

The Fresnel lens splits the direct from the diffuse solar radiation and can be combined with different solar radiation absorbers; solar thermal, photovoltaic or photovoltaic/thermal receptors can be adjusted to the solar concentrator to track the sun. The combined system can be used for effective lighting and temperature control of buildings or for other energy requirements according to the local weather conditions and the building needs. A PVT generator is studied because maximum operation flexibility can be reached with this type of receiver. The annual generation of thermal and electrical output energy is evaluated for Barcelona city in given climates and operational conditions. The optimum tilt angle expression derived shows to be useful in determining the best performance of the generator. An improvement above 5% is obtained when the optimum tilt angle is adopted instead of a value equal to the local latitude, the latter being traditionally used to maximize annual gain in solar installations.

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