Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 June 2018 doi:10.20944/preprints201806.0098.v1

Peer-reviewed version available at Energies 2018, 11, 1878; doi:10.3390/en11071878

# Effect of reflector geometry in the annual received radiation of low concentration photovoltaic systems

João Paulo N. Torres
Instituto de Telecomunicações,
Instituto Superior Técnico,
Universidade de Lisboa, Portugal.
joaotorres@tecnico.ulisboa.pt

Carlos A. F. Fernandes
Instituto de Telecomunicações,
Instituto Superior Técnico,
Universidade de Lisboa, Portugal
ffernandes@tecnico.ulisboa.pt

João Gomes
University of Gävle, Gävle, Sweden
jslcgomes@gmail.com

Bonfiglio Luc
Ecole Polytechnique
Univers. Montpellier, France
lucbonfiglio@gmail.com

Giovinazzo Carine
Ecole Polytechnique Universitaire de Montpellier, France
carinegiovinazzo@gmail.com

Olle Olsson
University of Gävle, Gävle, Sweden
olle@solarus.com

P.J.Costa Branco
LAETA, IDMEC,
Instituto Superior Técnico,
Univ. Lisboa, Portugal
pbranco@tecnico.ulisboa.pt

***Abstract*: Solar concentrator photovoltaic collectors are able to deliver energy at higher temperatures for the same irradiances, since they are related to smaller areas for which heat losses occur. However, to ensure the system reliability, adequate collector geometry and appropriate choice of the materials used for all their components will be crucial. The present study focuses on the re-design of the C-PV collector reflector currently produced by the Swedish company Solarus AB, together with a comparative analysis based on the annual assessment of the solar irradiance in the collector. An open-source ray tracing code (Soltrace) is used to accomplish the modelling of optical systems in concentrating solar power applications. Symmetric parabolic reflector configurations are seen to improve the PV system performance when compared to the conventional structures currently used by Solarus. The parabolic geometries, using either symmetrically or asymmetrically placed receivers inside the collector, achieve both the performance and cost-effectiveness objectives: for almost the same area or costs, the new proposals for the PV system may be in some cases 70 % more effective as far as energy output is concerned.**

***Index Terms* – C -PV solar systems, MaReCo, ray-tracing, reflector design, Soltrace.**

## I. NOMENCLATURE

| | | |
|---|---|---|
| $A_{apert}$ | aperture area of the collector | ($m^2$) |
| $A_{rcev}$ | receiver area | ($m^2$) |
| $C$ | concentration factor | (-) |
| $E_{flat}$ | Energy produced by the flat panel | (W.h) |
| $E_{new}$ | Energy produced by the new geometry | (W.h) |
| $E_{standard}$ | Energy produced by MaRECo structure | (W.h) |
| $G$ | gain or energy ratio | (-) |
| $N_{tot}$ | number of total rays in the simulation | (-) |

Greek Symbols

| | | |
|---|---|---|
| $\alpha_s$ | elevation solar angle | (º) |
| $\nu$ | incident angle | (º) |
| $\eta_E$ | electrical efficiency | (-) |
| $\theta_a$ | acceptance angle | (º) |
| $\theta_t$ | tilt angle of the glass cover | (º) |

*Acronyms and abbreviations*

| | |
|---|---|
| BP | Bypass |
| CPC | Compound Parabolic Concentrator |
| C-PV | Concentrating Photovoltaic |
| HC-PV | High Concentration Photovoltaic |
| LC-PV | Low Concentration Photovoltaic |
| MC-PV | Medium Concentration Photovoltaic |
| MaReCo | Maximum Reflector Collector |
| PV | Photovoltaic |
| PVT | Photovoltaic and Thermal |

## II. INTRODUCTION

Economics is currently referred as one of crucial aspect of sustainability, dealing basically with the energy efficiency. In 2011[1], electricity generated in Sweden from renewable energy sources reached 56.7% of total electricity generation[2], being ranked fifth in terms of percentage of electricity generated from renewable energy sources. Portugal appears in the seventh position, with around 47%. This paper is intended to expand a previous work of the authors [1] and it is organized as follows: section III summarizes the state of the art in concentrator photovoltaic (C-PV) collectors, with special emphasis on the conventional Solarus[3] low concentrating collectors, generally referred as Maximum Reflector Concentrator (MaReCo) structure; section IV describes the accomplished methodology to define the geometry of the C-PV collector related to the optical analysis tool designated by Soltrace[4]; section V makes a comparison, in terms of a cost-effectiveness analysis, between the conventional MaReCo Solarus configurations and the new configurations, which use symmetrical parabolic geometries for the collector reflector. The assessment takes into account the influence of the irradiance and the receiver

[1] Energy Policies of IEA Countries - Sweden, 2013 Review.
[2] Energy Balances of OECD Countries, IEA/OECD Paris, 2012.
[3] SOLARUS is a private company founded in 2006, headquartered in the Netherlands and with a R&D centre in Sweden (http://solarus.com).
[4] https://www.nrel.gov/docs/fy14osti/59163.pdf

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 June 2018 doi:10.20944/preprints201806.0098.v1

Peer-reviewed version available at *Energies* **2018**, *11*, 1878; doi:10.3390/en11071878

location inside the collector for different zones of the globe. Main conclusions are summarized in section VI.

## III. Photovoltaic solar systems

Together with environmental reasons, the current downward trend in prices of the solar cell manufacturing is dictating an important change in the world total energy consumption. Although, the hydrocarbon fuels will leader this domain in the next two decades, deep alterations became evident in the current annual average rate of the energy growth associated with different energy sources. Benefitting both from technical improvements and the use of optimized system designs [2], the costs of photovoltaic (PV) modules have dropped rapidly, forecasting levelized costs (value of manufacture+operating costs over economic life costs) around 0.1 dollars for the period 2016-20.

### *A. Concentrator photovoltaics*

C-PV technology can play an important role to achieve high levels of energy conversion performance in PV devices. Linking an optical device between the light source and the receiver/absorber, the efficiency of the collector energy conversion related to the photoelectric effect will be theoretically higher. The improvement will increase with the concentrator factor *C*, which represents the ratio of the total collected energy in the concentrator collector to the total energy collected in the flat collector. There are three different C-PV systems:

- Low concentration (LC-PV): *C* between 1 and 40 suns[5];
- Medium concentration (MC-PV): *C* between 40 and 300 suns;
- High concentration (HC-PV): *C* between 300 and 2000 suns.

Nevertheless, there are some disadvantages that shall be taken into account in concentrating systems. Namely:

- The concentration depends on the reflector, decreasing when the reflectivity decreases. This one should be as closer as possible of 100%. However, it should be kept in mind that in non-ideal situations, concentration carries the penalty of extra reflection losses on the reflector (normally ranging from 3% to 20%, depending on the reflector type).
- In single or multiple reflections, the redirection of the rays can lead to a situation in which light does not reach the target (receiver), leading to a decrease of the collector efficiency.
- Concentrator collectors usually absorb little diffuse radiation. Therefore, the collector should be adequately oriented towards the incoming beam radiation from the sun, which means that, for an effective energy collect, a tracking system is desirable, with the unavoidable additional costs associated.

Stationary collectors normally present *C* up to 5. On the other hand, tracking collectors can reach very high concentration factors and, over the year, they are able to receive more solar radiation in the absorber than non-tracking collectors [3]. However, tracking systems are more complex and they are related to higher installation and management costs. Compromises will be taken in account, following which the final decision will be made: stationary collectors will yield less energy per absorber area but they are also less expensive. Solarus standard collectors are non-tracking type.

Along with partial shading, related to several effects (clouds, reflector boundaries, shadows, dust or any sort of dirtiness), the use of reflectors in stationary solar C-PV collectors normally cause non-uniform distribution of light along the string of PV cells in the receiver. This may lead to hot spots and cause aging or permanent damage to the cells. When cells are completely shaded (by inadequate design of the system), the hot spot evidence may prevent the triggering of the bypass (BP) diode, resulting in increased temperature that will degrade the solar panel.

In mismatching operating conditions (due to aging, manufacturing tolerances, different orientation of the solar panels…), the energetic efficiency of the PV systems is strongly compromised. To mitigate these effects, a re-design searching for alternatives concerning the geometry of the C-PV collectors is imperative [4-5]. A brief summary of C-PV state of the art can be found in [6-7].

### *B. Solarus C-PV collector*

Solarus concentrator collector is hybrid (PV plus thermal, or PVT), operates without a tracking system [8] and it is specially designed for roof applications in northern countries in Europe. The PVT Solarus collector belongs to the compound parabolic collector (CPC) type, which is commonly known as the maximum reflector concentrator (MaReCo) family [9], and it is widely described in the literature [10-12]. It is formed by a reflector with two asymmetrical truncated parabolic sections separated by a circular section (compound parabolic concentrator, CPC), a flat receiver with solar cells in both sides and bi-facial absorbers. The MaReCo concept can be used for various conditions, as roof, wall or stand-alone installations. In the former, it has the glass cover parallel to the roof surface and the trough axis is parallel to the ground and normally extended in the east-west direction. It Sweden, the collectors are adapted for high latitudes in south-facing roofs and to the considerable variation of solar distribution from season to season. But they can be matched to other conditions. The electric part of the each module consists of strings of 38 series-connected cells of 1/6 type or 19 series-

[5] Sun represents the number of times that the solar light is concentrated. 1 sun corresponds to standard illumination at AM1.5, or $1000W/m^2$.

 doi:10.20944/preprints201806.0098.v1

Peer-reviewed version available at *Energies* **2018**, *11*, 1878; doi:10.3390/en11071878

connected cells of 1/3 type[6]. The panel has several parallel connected strings distributed over two similar troughs. For example in Fig.1, there are 152 PV solar cells of 1/6 type. All dimensions are expressed in mm. The length of the receiver $L_r$ is 148 mm; the aperture length $L_{aper}$ is 192 mm. Water connection for cooling is represented in blue; electric connections are represented in red.

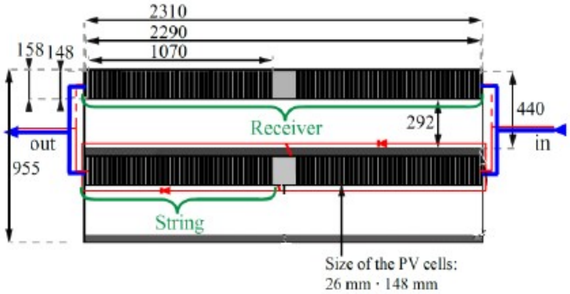



Fig. 1. Top view of the PVT Solarus AB panel.

Some structural parameters that describe the collector are schematically shown in Fig.2.

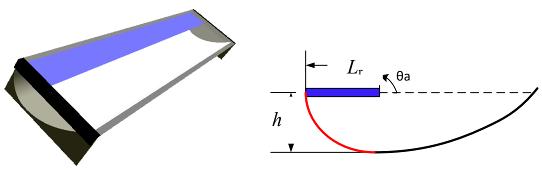



Fig. 2. *Standard* Solarus C-PVT collector

Other parameters related to the location and installation details of the solar panel are equally important for its complete description: the latitude (N or S), the longitude (W or E), the elevation solar angle $\alpha_S$, the tilt $\theta_t$ and the azimuthal angle $\gamma$ (Fig. 3).

The solar radiation is concentrated into the thermal absorber by the aluminium reflector. The acceptance angle for the reflector is defined by the optical axis direction related to the reflector.

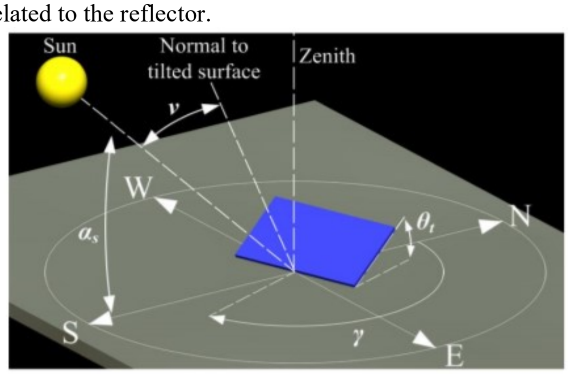


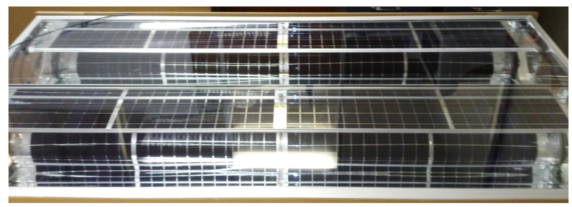

Fig. 3. Schematic representation of the azimuthal, altitude and tilt angles for a given solar cell panel.

[6] The standard cell is 0.156×0.156 m$^2$. To fit the collector design, the cell is cut to 0.148×0.156 m$^2$. When the larger dimension is cut into 3 slices, it results a solar cell known as 1/3 cell, whose area is 0.148×0.052 m$^2$; if it is divided into 6 slices, a solar 1/6 is formed (0.148×0.026 m$^2$).

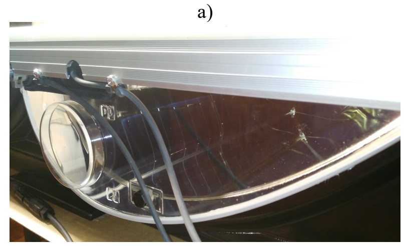
The optical efficiency of the collector changes throughout the year depending on the projected solar altitude. The tilt of the collector (the angle that the glass cover of the collector makes with ground) determines the amount of total annual irradiation falling within the acceptance interval. The aperture area corresponds to the opening through which sun's rays enter.

For MaReCo collectors, the concentration factor $C$ is given by the ratio between the aperture area of the collector and the receiver area [10].

Considering anisotropic light sources (a combination of beam and diffuse light), the concentrator factor related to typical MaReCo Solarus structures is roughly 1.4 to 1.5 suns. Hereafter this geometry will be referred as *standard*. It is schematically represented in Fig.1. Photos with the top and side views are shown in Fig.4.



a)



b)

Fig. 4. Solarus C-PVT panel; a) the top view; b) side view.

Some features of the standard Solarus C-PVT collector are described below:

- $C$ = 1.87 (backside only);
- Total aperture area = 2.09 m$^2$ ;
- Total receiver area = 1.45 m$^2$;
- Acceptance angle, $\theta_a$=90º.

In order to reach new markets and gain competitiveness against standard PV and T, a new Solarus reflector design for lower latitudes was conceptualized and simulated. These new reflector designs also had a new receiver design which is 56mm wide and 2310 mm long, as shown in Fig.5.

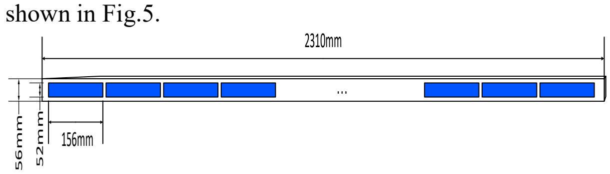



Fig. 5. Absorber of the standard Solarus collector.

Peer-reviewed version available at Energies 2018, 11, 1878; doi:10.3390/en11071878

The solar collector uses reflector material made of anodized aluminum[7]; the glass cover of the collector is made of low iron glass[8]. The main optical properties of the reflector, glass and plastic gables may be shown in Table 1.

TABLE 1
SUMMARY OF THE PROPERTIES OF OPTICAL ELEMENTS

| Optical elements | Optical properties |
|---|---|
| Reflector | Reflectance[9] = 95% |
| Glass | Transmittance[10] = 95%<br>Refractive index = 1.52 |
| Plastic gables | Transmittance = 91%<br>Refractive index = 1.492 |

## IV. METHODOLOGY: EFFICIENCY CALCULATIONS AND COLLECTOR GEOMETRIES

Understanding the conversion processes that are associated with solar resources requires specialized modelling tools to predict system and economic performances. One of the most important aspects concerns the collector design. For energy calculations in the receiver ray tracing software (Soltrace, Tonatiuh) are often used. A detailed description of the adopted procedure for asymmetric Solarus collectors (Tonatiuh) can be found in [9]. In this paper, Soltrace software was used. Since the early 1960´s, when the first general ray-tracing procedures were described [13], a long road has been travelled, due to the need for designing and modelling solar concentrating systems. From the late 1980´s several optical specific commercial design codes have been developed by the National Renewable Energy Laboratory (NREL), but they were not general and flexible enough for a suitable analysis: a deeper insight into physical and engineering aspects was required. Based on a Monte-Carlo methodology, Soltrace was the answer. Basically, $N_{tot}$ solar rays are traced from the sun through the system, towards the aperture area of the collector, while encountering various optical interactions. It is assumed that each photon arriving to each side of the receiver generates electricity. Accuracy increases with $N_{tot}$, but the use of larger ray numbers means more processing time. A compromise shall be taken, accordingly to the desired result and the situation under analysis. For instance, relative changes in the optical efficiency for different sun angles is not as exigent (as far as $N_{tot}$ is concerned) as when one needs a more accurate assess to the flux distribution on the receiver. The particular site latitude and time (day of the year and local solar hour) shall be included in the set of data. From this information, the sun position is calculated (azimuth and elevation). The simulation analysis will allow the collected solar annual energy in each new structure to be assessed and compared to the standard C-PVT Solarus collector. The gain [14] is given by:

[7] Alanod, Reflector manufacturer, 2013. http://alanod.com
[8] SunArc, Solar glass manufacturer, 2013. http://www.sunarc.net/
[9] Measured according to norm ASTM891-87.
[10] Measured according to norm ISO9050 for solar thermal.

$$G = \frac{(E_{new} - E_{standard})}{E_{standard}} \quad (1)$$

where $E_{new}$ and $E_{standard}$ are the annual energy received per m² concerning the new CPC design and the standard Solarus collector, respectively. Positive gains mean that the new reflector shape has a better performance than the current Solarus shape. The concentration factor for 2D concentrating systems (linear: parabolic, circular, MaReCo trough collectors) is given by:

$$C = \frac{1}{2\,\mathrm{Sin}(\theta)} \quad (2)$$

For MaReCo with acceptance angles of 90º, $C$=1.414. According to [9], and using geometrical considerations, the linear concentrating factor is given by:

$$C = \frac{A_{apert}}{A_{rec}} \quad (3)$$

In (3), $A_{apert}$ and $A_{rec}$ are the aperture and the receiver areas, respectively. Taking into account the values referred in section III.B for standard collector in section III.B, the concentration factor is around 1.44. Nevertheless, lower acceptance angles shall increase $C$. Although, concentration reduces the costs, it also reduces the annual output. Due to the reflection losses, a CPC collector will always receive less energy per m² of aperture than a flat receiver. The annual energy percentage $\eta_E$ of a CPC collector is the ratio between its annual received energy per unit area and the one concerning a flat collector ($E_{flat}$)

$$\eta_E = \frac{E_{new}}{E_{flat}} \quad (4)$$

The target is a percentage value as high as possible. To reach to a new design that receives nearly as much as the flat collector, but at lower costs, will represent an upgrade. Three new geometries were proposed for lower latitudes[11]. Two of them present pure symmetric geometries (parabolic reflector and receivers symmetrically placed) and the third has a parabolic reflector but with an asymmetrically placed receiver as standard MaReCo (truncated CPC with a bifacial receiver plus parabolic and circular reflectors). The increase of symmetry in the geometry is expected to improve the collector performance for lower latitudes, where the difference between winter and summer solar radiation is not so large as in Sweden. All collectors present the same height and aperture area (Fig.6).

## V. RESULTS

The results presented in this section were obtained using Soltrace software. In the simulations, it has been assumed that the collector model is ideal. This means that:

[11] In the presented examples, simulations were carried out for Lisbon (Lat=38º,42'N, Long=9º,8'W) and Luanda (Lat= 8º,50´S, Long=13º,14´E)

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 June 2018 doi:10.20944/preprints201806.0098.v1

Peer-reviewed version available at Energies 2018, 11, 1878; doi:10.3390/en11071878

(i) the optical properties are ideal (no optical errors); (ii) the reflectivity of the reflector is 100% (against 95% with Alanod reflector); (iii) the plastic gables, frame, glass cover were not drawn in the 3D model; (iv) the thickness of the absorber is quite negligible (2 mm), whereas the current absorber is around 1.14 cm.

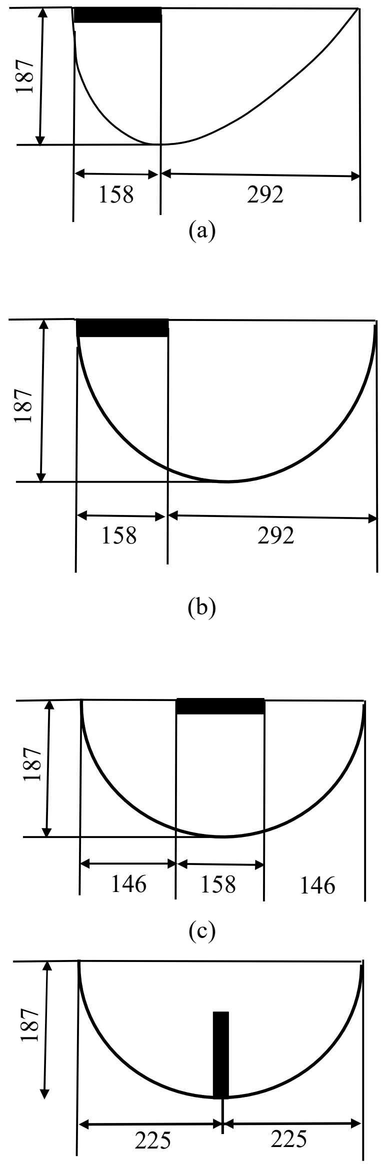



Fig. 6. Collector structures
(a) P1- standard MaReCo;
(b) P2- Parabolic Reflector; Asymmetric Receiver
(c) P3- Parabolic Reflector; Symmetric Horizontal Receiver
(d) P4- Parabolic Reflector; Symmetric Vertical Receiver

### A. SOLARUS C-PV COLLECTOR

Three latitudes were considered (Gavle, Lisbon and Luanda) for two situations (winter and summer solstices) for the four geometries (standard and symmetric/asymmetric parabolic). Validation of the methodology described in section IV was settled by comparison with the simulation results concerning current Solarus solar panels presented in [14], which use Tonatiuh software. Results related with the solar panel efficiencies are presented in Fig.7 when the tilt of the panel is zero. It is apparent that, as far as Lisbon is concerned, the best solution, in a collected energy per time basis, corresponds to P4, the symmetrical collector with a vertical receiver. This structure presents the highest values, for both solstices. In spite of being a good solution for winter solstice, geometry P3 has a poor performance during the Summer solstice in Lisbon, due to the high elevation solar angles.

The lateral collected power, which is more clearly seen during the winter solstice in Gavle and Lisbon, is associated to the transparent gambles in all existent structures (photos of Fig. 4, concerning the double trough C-PVT Solarus panel).

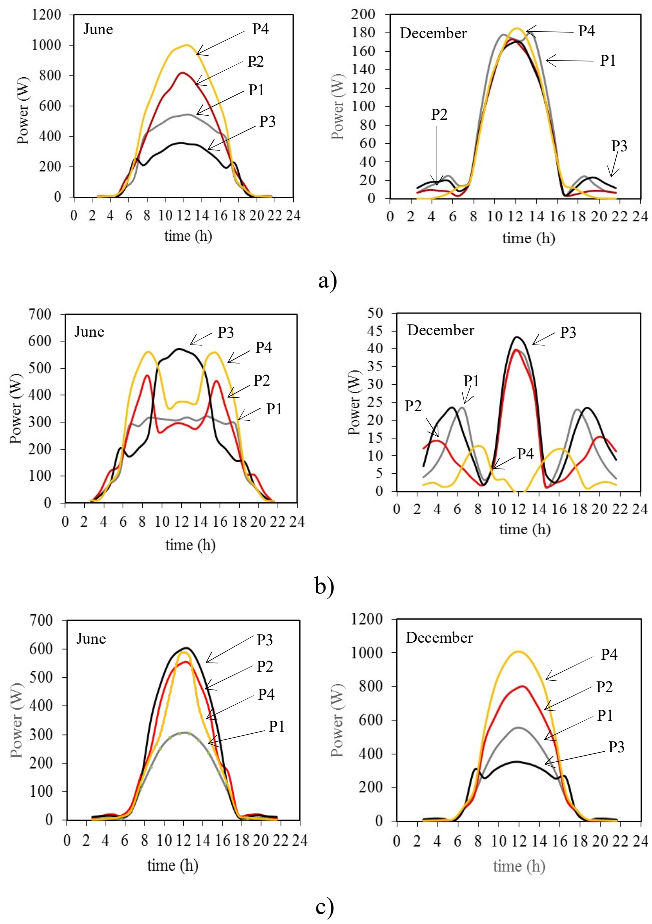



Fig.7. Collected energy per time along the solstices for the standard and proposed structures, when tilt is zero in a) Lisbon, b) Gavle c) Luanda. P1-standard MaReCo ; P2- Parabolic Reflector; Asymmetric Receiver; P3-Parabolic Reflector; Symmetric Horizontal Receiver; P4-Parabolic Reflector; Symmetric Vertical Receiver.

Considering Gavle for null tilt, the best option presented in Fig. 7 is the P3 structure. It is worth noticing, that P4 is also a good solution for summertime. The distribution along the day in this case is more uniform,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 June 2018 doi:10.20944/preprints201806.0098.v1

Peer-reviewed version available at *Energies* **2018**, *11*, 1878; doi:10.3390/en11071878

which is advantageous for the beginning and the end of the day, where the demands should be higher for grid or off-grid habitation segments or markets. However, around winter solstice, the produced energy per time almost vanishes in P4, due to the small elevation solar angles. Therefore, this solution shall be discarded.

As far as Luanda is concerned, and reminding that this city is located in the south hemisphere, on the 21st December the Sun will be higher than on the 21st June. This justifies the fact that during December, P3 is not a good option, in spite of presenting a good performance in June. Some other conclusions may be highlighted, for example, the fact that: (i) P4 geometry is adequate for both solstices and (ii) standard Solarus collectors represent bad solutions for locations near the equator.

The collector tilt variation has a big influence on the panel efficiency. For Gavle it has been referred that the increase of tilt angles can lead to important improvements, being the best performances achieved for tilts around 30º [15]. However, for tilts greater than 45º, due a deep decrease of the acceptable angles during Summer solstice, the collected energy almost vanishes, leading to a cut-off phenomenon [16]. By a comparative analysis of the geometries under study, and considering the case of Gavle, it is apparent from Fig.8 that geometry P4 is the best option, presenting good performances either in Summer or in Winter, whereas P2 is good in Winter but less good in Summer. For a tilt of 30º, the P4 geometry shows, according to (1), positive gains in Gavle that can reach 70%, being similar to the results presented in Lisbon for a more disadvantageous situation (tilt 0º), as seen in Fig.7.a).

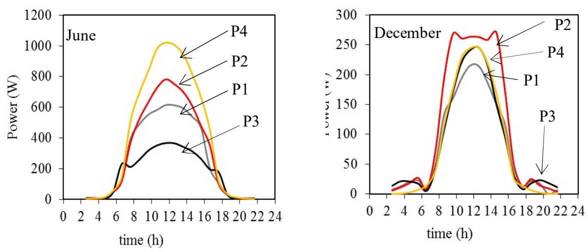



Fig. 8. Collected energy per unit time along the solstices for the standard and proposed structures, when tilt is 30º in Gavle.

### B. Potential Choices

The simulation results have shown that for all situations, there is always at least one of the new proposals that presents better performances than the standard Solarus C-PV collector.

For example, in Lisbon with tilt 0º or in Gavle with tilt 30º, using the maximum values of energy per unit time (around midday), the proposed configuration P4 reaches gains around 70%.

Using (4), it is straightforward to show that:

$$\frac{E_{new}}{E_{s\tan d}} = \left(1 + \eta_E\right) \quad (5)$$

So, an increase of 170% in the colected energy is foreseen in Gavle in the summer solstice for a symmetric C-PVT structure with horizontal receiver and a tilt of 30º (Fig.8).

It is also worth referring, that all the proposed configurations have the same total collector area than the standard Solarus, which means that the involved costs are practically the same. Notice that costs represent an important issue for industrial applications.

Finally, it should be highlighted that the option(s) to be taken or the final decision depend definitevely on the client's demands.

## VI. Conclusion

Alternative geometries for C-PV collectors have been studied using ray trace software Soltrace. In this paper, it has been considered three locations (Gavle, Lisbon and Luanda) and simulation analysis have been presented for winter and summer solstices. A comparative analysis with the currently MaReCo Solarus C-PVT has been assessed. In all situations, there was at least one of the new proposals that correpond to an improvement of the power production when compared to the standard Solarus collector (170% in some cases!).

The simulation method using Soltrace is in fact an important tool to investigate the impact of the collector geometry on the effective solar radiation in a simpler, faster and cheaper way than the experimental methods, which recur to expensive prototypes. These results are important input data for the complete description of the collector both electrically (strings of cells in the receiver) and thermally (absorber with the pipes and the the fluid to remove heat) [17].

These studies reveal crucial to the manufacturers in order to reach emergent markets. Current investments and commitments must be made to further objectives in a next future. Compromises will always be taken into account, following which the final decision will be made.

## Acknowledgement

This work was supported by FCT, through IDMEC, under LAETA, project UID/EMS/50022/2013 and under IT, project UID/EEA/50008/2013.

## References

[1] J. Gomes, B. Luc, C. A. F. Fernandes, J. P. N. Torres, O. Olsson, P. J. C. Branco, S. K. Nashih, "Analysis of different C-PVT reflector geometries", IEEE Internationa Power Electronics and Motion Control Conference (PEMC), 2016.

[2] T. Razykov, C. Ferekides, D. Morel, E. Stefanakos, H. Ullal and H. Upadhyaya, "Solar photovoltaic electricity: Current status and future prospects", *Solar Energy* , vol.85, 8, pp. 1580–1608, 2011.

[3] P. Pérez-Higueras, E. Muñoz, G. Almonacid and P. Vidal, "High-concentrator photovoltaics efficiencies: present status and forecast", *Renewable and Sustainable Energy Reviews, Elsevier*, vol.15, pp. 1810-1815, 2011.

[4] P. Carotenuto, S. Curcio, P. Manganiello, G. Petrone, G. Spagnuolo and M. Vitelli, "Algorithms and devices for the dynamical

reconfiguration of PV arrays", *PCIM Europe-2013*, pp. 765-772, 2013.

[5] M. Balato, L. Constanzo and M. Vitelli, "Multi-Objective Optimization of PV arrays performances by means of the dynamical reconfiguration of PV modules connections", in 4th *International Conference on Renewable Energy Research and Applications*, pp..1646-1650, 2015.

[6] Carlos A. .F. Fernandes, João Paulo N. Torres, P. J. Costa Branco, João Fernandes and João Gomes, "Cell string layout in solar photovoltaic collectors", *Energy Conversion and Management, Elsevier*, vol. 149, pp. 997–1009, 2017.

[7] A. Adsten, A. Helgesson and B. Karlsson, "Evaluation of CPC-collector designs for stand-alone, roof- or wall installation", *Solar Energy,* vol. 79, 6, pp. 638-647, 2005.

[8] A. Monika, "Solar Thermal Collectors at High Latitudes, Design and performance of non tracking Concentrators", Ph.D. Thesis, Upsala University, 2012.

http://pointfocus.com/images/pdfs/csphighlatitude.pdf

[9] R. Bernardo, H. Davidsson and B. Karlsson, "Performance Evaluation of a High Solar Fraction CPC-Collector System", *Japanese Society of Mechanical Engineers - Journal of Environment and Engineering*, vol. 6, pp. 680-692, 2011.

http://dx.doi.org/10.1299/jee.6.680

[10] R. Bernardo, B. Perers, H. Håkansson and B. Karlsson, "Performance Evaluation of Low Concentrating Photovoltaic/ Thermal Systems: A Case Study from Sweden", *Solar Energy*, vol. 85, pp. 1499-1510, 2011.

[11] R. Bernardo, H. Davidsson, N. Gentile, C. Mumba and J. Gomes, "Measurements of the Electrical Incidence Angle Modifiers of an Asymmetrical Photovoltaic / Thermal Compound Parabolic Concentrating - Collector", *Scientific research, Engineering*, 5, pp.37-43, 2013. doi: 10.4236/eng.2013.51B007

[12] B. Karlsson and G. Wilson, "MaReCo design for horizontal, vertical or tilted installation", *Vattenfall Utveckling AB (Contribution to Eurosun 2000 in Copenhagen), 2000*.

[13] G. Spencer and M. Murty. "General ray-tracing procedure." *JOSA* vol. 52(6), pp. 672– 676, 1962.

[14] José Moreno Puerto, "Performance evaluation of the Solarus AB asymmetric concentrating hybrid PV/T collector", MSc. Thesis, University of Gavle, Sweden, 2014.

[15] L. Diwan, "Study of Optimizations in a Novel Asymmetric Photovoltaic/Thermal Hybrid Solar Collector", MSc. Thesis, Instituto Superior Técnico, Lisboa, 2013.

[16] C. Giovinazo, L. Bonfiglio, J. Gomes and B. Karlsson, "Ray Tracing model of an Asymmetric Concentrating PVT", *Eurosun 2014*, pp.16-19, 2014.

[17] M. Hossain, R. Saidur, H. Fayaz, N. Rahim, M. Islam, J.Ahamed and M. Rahman., "Review on solar water heater collector and thermal energy performance of circulating pipe", *Renewable and Sustainable Energy Reviews, Elsevier*, vol.15, 8, pp. 3801-3812, 2011.