Design of an inverted absorber compound parabolic concentrator for solar air heating

Fernando S. Guerreiro[a *], Mick Mc Keever[a,b], David Kennedy[a,c], Brian Norton[a]

[a]Dublin Energy Lab, Dublin Institute of Technology (DIT), Dublin, Ireland
[b]School of Electrical and Electronic Engineering, DIT, Dublin, Ireland
[c]School of Mechanical Engineering, DIT, Dublin, Ireland

Abstract: A building integrated solar air heating collector with an asymmetric compound parabolic concentrator is designed to receive solar insolation for at least 8 hours a day during summer periods in Ireland. Optical analysis was performed based on ray tracing technique to maximise absorbed thermal energy received by an inverted transpired absorber. Two design constraints were to minimise the amount of reflector material and minimise the amount of mutual shading when multiple collectors are stacked above each other on a building facade. Based on the scale and size of the optical concentrator developed, the system has the potential application for pre-heating fresh for buildings and solar drying.

1. Introduction

Solar energy air heating systems are important as the air is often the final carrier of the thermal energy in many applications: space heating of buildings and dwellings, timber seasoning, and drying of agricultural products (Alta et al., 2010). Concentrating solar collectors can deliver hot air flow at temperatures higher than those from flat-plate collectors (Duffie and Beckman, 2013). However, as the concentration ratio increases, they collect a smaller part of any diffuse solar radiation received through their aperture areas (Welford and Winston, 1989). Theoretical and experimental analyses have been undertaken in relation to Asymmetric Inverted Absorber Compound Parabolic Concentrating (IACPC) collectors with the aim of suppressing heat losses by placing the absorber horizontally and facing towards the ground (Rabl, 1976). An IACPC was designed to be used as a solar air heater collector by Shams (2013). This collector had a perforated absorber surface made of carbon fibre placed at a fixed cavity height, a glazed aperture, a concentration ratio of 2.0, and was optically characterised and experimentally tested at different air flow rates.

The design and analysis of solar concentrators are mostly based on ray tracing techniques that trace the path of the light represented by multiple straight-line elements (Welford and Winston, 1989). This approach can provide relevant information regarding the collector's performance, such as:

- Average number of reflections before the incoming rays reach the absorber plate;
- Beam optical efficiency as a function of the incidence angle;
- Visualisation of the ray's path and reflection points (Mallick et al., 2007);
- Intensity of energy distributed along the absorber surface (Shams, 2013);
- Characterisation of the system's optical behaviour for thermal modelling and simulation;
- Comparison of the optical performance between two systems (Zacharopoulos et al., 2000).

The objective of this paper is to define the optimal geometry of an air heater IACPC collector with a perforated absorber, using ray tracing optical modelling.

*Corresponding author.
E-mail address: fernando.guerreiro@mydit.ie (F.S. Guerreiro).

2. Methodology

2.1 Collector specifications

The collector is a combination of an inverted perforated (transpired) absorber and asymmetric compound parabolic concentrator (ACPC), as shown in Fig. 1 and Fig. 2.

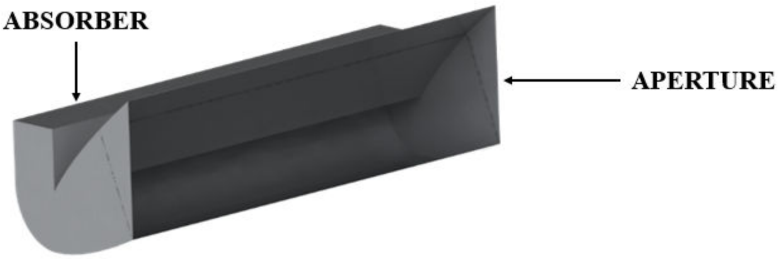

Fig. 1. Isometric view of the IACPC collector to be designed

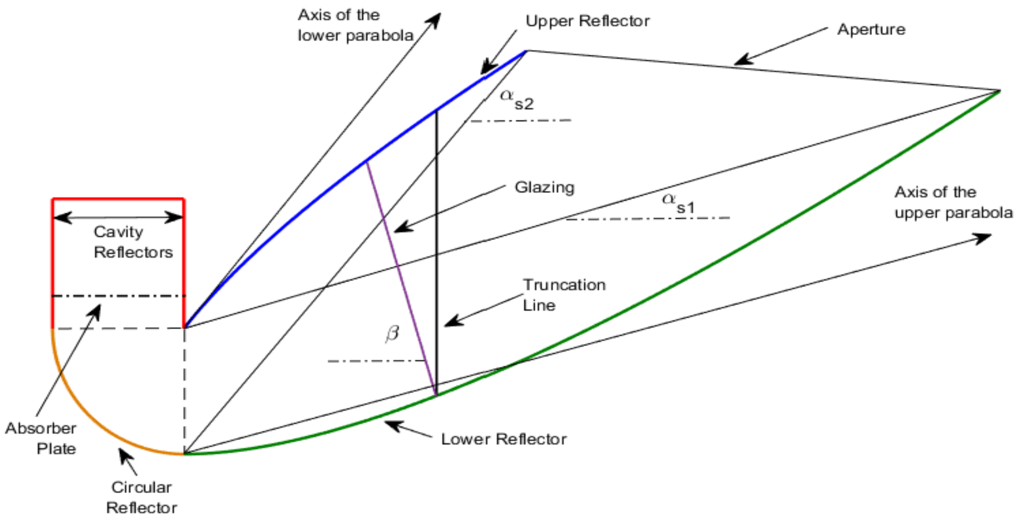

Fig. 2. Solar collector cross section

The reflector can be considered in three sections:

- Primary section: This consists of two asymmetric parabolic reflectors that reflect solar rays coming through the aperture and concentrates them to the secondary section;
- Secondary section: This comprises of a circular reflector, responsible for reflecting all the incoming rays upwards towards the tertiary section;
- Tertiary section: This consists of a cavity composed of two vertically straight reflectors that receives part of the solar rays from the secondary section and directs them towards the absorber surface. This section has a function of keeping the convection suppressed at the absorber due to the formation of a thermally stratified air layer within the cavity (Eames et al., 1996).

The absorber surface is perforated to allow the airflow to be entrained by the action of a fan through the holes, thus transferring heat from the absorber to the flow (Shams, 2013).

The aperture at the vertical position (at the truncation line indicated in Fig. 2) has been set as 330 mm (W_{apt}) in width to be able to mount three collectors on a wall per meter of height therefore avoid mutual shading. The glazing placed in the primary section works as a heat trap, protecting the interior of the unit against the weather. Its position at a given inclination β seeks to maximise glazing transmittance.

Considerations have also been given to the angles of the axes of both parabolas (α_{s1} and α_{s2}), which influence the primary section shape. The selection of such variables must take into account the compromise between optical efficiency and concentration ratio (ratio of aperture area to absorber area) to collect more solar radiation.

Besides the variables previously mentioned, there is a minimum design requirement for the collector's full operation for 8 hours a day over the summer (93 days) in Dublin (53º latitude), from 8am to 4pm. This means that all incoming direct solar radiation between the altitude angles of 17º and 60º must be concentrated and be received at the transpired absorber plate.

2.2 Optical Modelling

For the optical analysis, a 2D ray tracing algorithm was developed from first principles and implemented in Matlab®. The model calculates the path each specular ray follows from entry to exit for a shape and size of reflector. The following assumptions were made in the model:

- All reflectors are specular;
- The reflector reflectance (ρ) is 0.95;
- 3300 equally spaced solar rays were used, each one carrying equal amount of energy (E);
- The absorber absorptance (α_{abs}) is 0.85;
- 4-mm thick glass, with refraction index of 1.526 and extinction coefficient of 4 m^{-1}. Its transmittance (τ_g) was calculated from equations described in Duffie and Beckman (2013).

The beam optical efficiency is the ratio between the absorbed energy and the incoming energy. This efficiency as a function of the solar altitude angle α_P and the incident angle θ is calculated from:

$$\eta_B = \frac{\sum_{i=1}^{3000} \rho^{n_i} \tau_g(\theta) \alpha_{abs} E_i}{\sum_{i=1}^{3000} E_i} \tag{1}$$

where n_i is the number of reflections of the solar ray i. The incident angle is the angle between the solar altitude and the normal line to the glazing surface and was calculated from:

$$\theta = \alpha_P - (90 - \beta) \tag{2}$$

Considering the full operation requirement in the summer, Eq. (3) gives the mean optical efficiency within the solar altitude angle range (17º – 60º):

$$\eta_{MO} = \frac{\sum_{j=17^o}^{60^o} \sum_{i=1}^{3000} \rho^{n_i} \tau_g(\theta) \alpha_{abs} E_i}{\sum_{j=17^o}^{60^o} \sum_{i=1}^{3000} E_i} \tag{3}$$

The global optical efficiency η_{GO} defined as the fraction of incident solar energy measured at the site throughout all the period analysed – 8 hours a day (28800 seconds) for 93 days – is given by (Goswami, 2015):

$$\eta_{GO} = \frac{\sum_{m=1}^{93}\sum_{k=1}^{28800} \rho^n \tau_g \alpha_{abs} \left[G_{B,mk} \cos\theta_{mk} + \frac{G_{D,mk}}{C} \right]}{\sum_{m=1}^{93}\sum_{k=1}^{28800} \left[G_{B,mk} + G_{D,mk} \right]} \tag{4}$$

where G_B is the beam or direct radiation, G_D is the diffuse radiation, and C is the concentration ratio. The diffuse radiation distribution across the sky was assumed to be isotropic, which implies that the amount of diffuse component reaching the absorber is directly proportional to 1/C (Rabl, 1976). The data of G_B and G_D are from 2014 and 2015 in Dublin. The total absorbed energy S_T was calculated from Eq. (5), whose units are in MJ per m^2 of absorber:

$$S_T = G_T \eta_{GO} C \tag{5}$$

where G_T is the total solar radiation from those periods. This optical analysis did not include the tertiary section. For the collector's design, the reflector's height of the tertiary section will have the value of the absorber width.

3. Results and Discussion

To achieve the optimum design, the analysis started from the collector with the following characteristics: α_{s1} = 17º, α_{s2}= 60º, collector length of 1250 mm and β = 90º (vertical position). From this, variations in β and α_{s2} were investigated to find the final design subject to two constraints: minimum reflector material and minimum mutual shading when the systems are stacked on top of each other. Using SolidWorks®, an initial design was sketched (Fig. 3) and from this, the absorber width was found with the aim of achieving the maximum concentration ratio. Hence, the absorber width (W_{abs}) is 145 mm with the concentration ratio of 2.276.

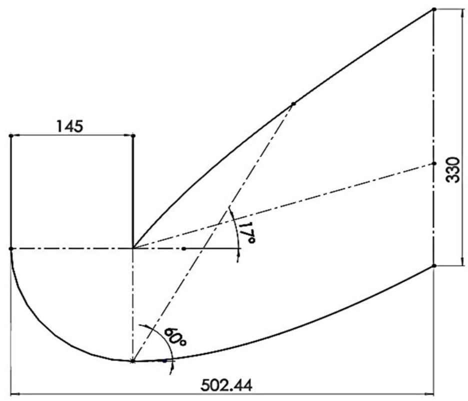

Fig. 3. Collector's initial design (mm)

Once the concentration ratio of the collector was set, the ray tracing algorithm was used to find the optimal glazing inclination that maximises S_T. It is evident that, at this inclination, there is the smallest energy loss through the glass. Fig. 4 and Fig. 5 show the variation of S_T and η_{MO} as function of β and α_{s2} respectively.

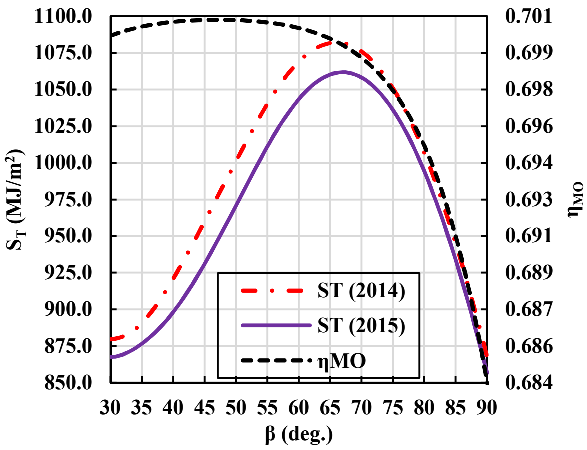

Fig. 4. Total absorbed energy and mean optical efficiency versus glazing inclination

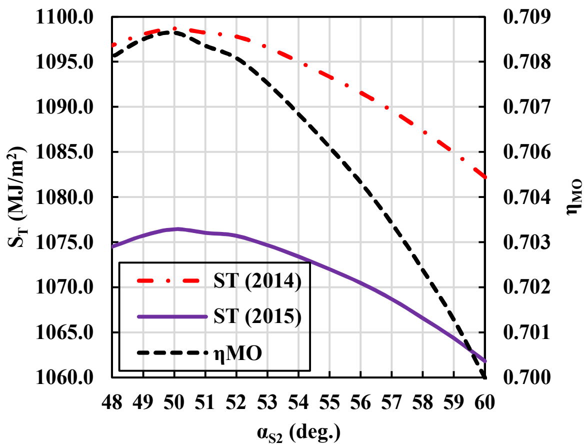

Fig. 5. S_T and η_{MO} versus angle of the lower parabola axis. Glazing inclination of 66°

From Fig. 4, the optimum inclination is approximately 66°, leading to η_{MO} of 0.6998 and S_T of 1082 MJ/m^2 from 2014 data and 1062 MJ/m^2 from 2015 data. Compared to the initial design (β = 90°), S_T from the average of 2014 and 2015 was raised by almost 25% and η_{MO} by approximately 2.3%. It was also observed that the inclinations that result in the highest values of mean optical efficiency (whose maximum is 0.7008) are close to 53°. However, the position at these inclinations does not provide the highest amount of total absorbed energy.

From Fig. 5 it is noted that the influence of α_{s2} on S_T and η_{MO} is less significant than that of β on the same dependent variables. The highest values were achieved at α_{s2} = 50°. At this condition, S_T = 1099 MJ/m^2 from the 2014 data, S_T = 1076 MJ/m^2 from the 2015 data and η_{MO} = 0.7086, increasing by 1.41% in S_T and 1.26% in η_{MO} compared to the variables at α_{s2} = 60°. The variation of α_{s2} also influences the shape of the parabolic reflectors, as observed in Fig. 6. For the cost, the calculations were performed based on a reflector sheet price of €50/m^2 provided by the company ALANOD.

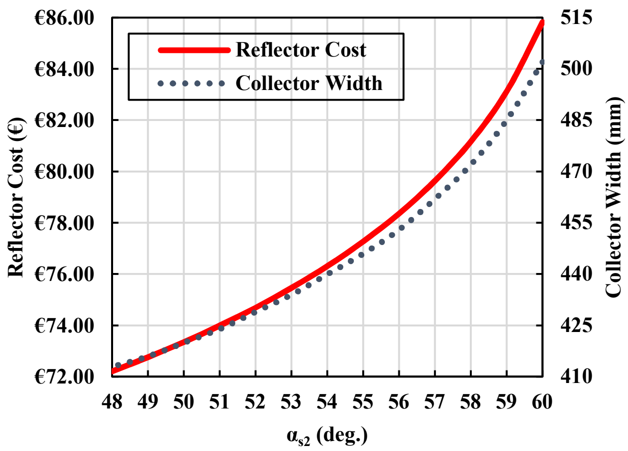

Fig. 6. Reflector cost and collector width *versus* angle of the lower parabola axis.

As shown in Fig. 6, as α_{s2} decreases, the collector becomes smaller, lighter, and less expensive. This is due to the parabolic shape modifications caused by the rotation of the lower parabola axis. The reflector cost reduces from nearly €86 at α_{s2} = 60° to €73.35 at α_{s2} = 50°, reducing by 14.5% of the initial design cost. Hence, the reduction of α_{s2} to 50° is positive in terms of absorbed energy and material cost savings.

From the design variables found by optical analysis, Table 1 depicts the values of the geometry parameters and Fig. 7 presents the final collector's dimensions and shape.

Table 1. Geometric parameters of the final design

Geometry Parameter	Value
Aperture Width	330 mm
Absorber Width	145 mm
Concentration Ratio	2.276
Glazing Width	270 mm
Glazing Inclination	66°
Collector Length	1250 mm
Collector Width	424 mm

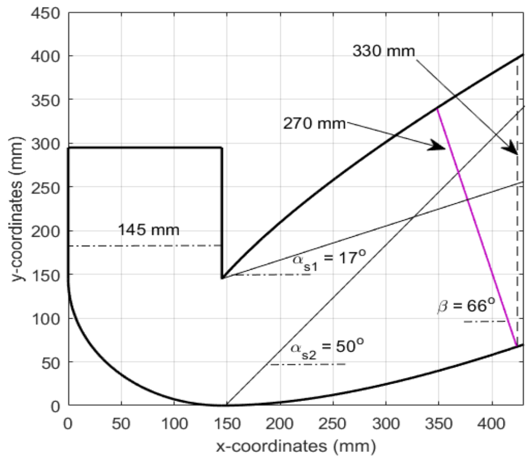

Fig. 7. Cross section with dimensions of the solar collector to be fabricated

The optical characterisation of the final design in terms of η_B , angular acceptance, glazing transmittance, and reflection efficiency as functions of altitude angle is shown in Fig. 8. The reflection efficiency takes into account only the effect of the average number of reflections.

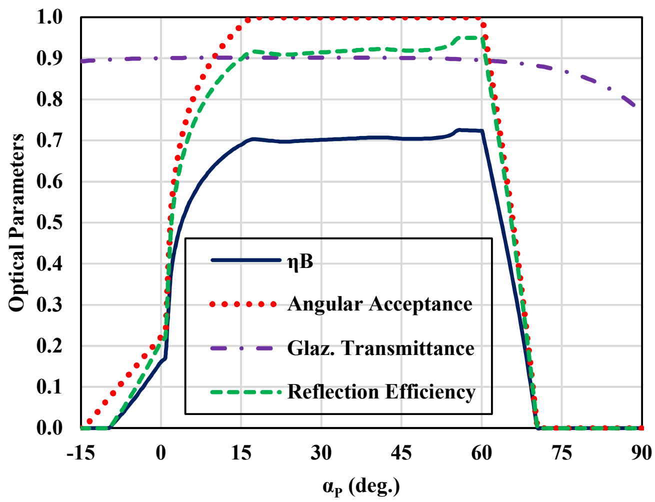

Fig. 8. Optical parameters versus solar altitude angle

At the range of 17º – 60º of solar altitude angles, all the incoming rays reach the absorber and η_B lies between 0.6970 and 0.7255. The highest values of η_B are between 55º and 60º of α_P, which is explained by the least number of reflections at the reflectors expressed by the curve of reflection efficiency. The glazing inclination kept the transmittance at 0.9 within the solar altitude range, which minimised the losses through the glass.

The ray tracing illustrated in Fig. 9 visualise how the incoming rays reach the absorber surface.

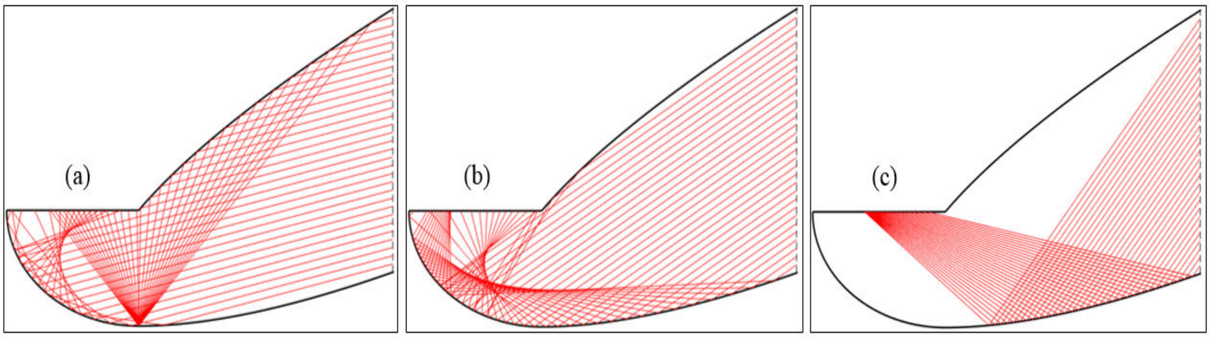

Fig. 9. Graphic results of ray tracing for solar altitude angle of (a) 17º, (b) 39º and (c) 60º

In Fig. 9(a) the rays enter the collector at 17º solar altitude angle which is the lower limit of the requirement and α_{s1} = 17º. All the rays incident on the upper parabolic reflector converge to its focal point, at the intersection of the lower parabola and the circular reflector. In Fig. 9(c) where α_P is 60º, is the upper limit representing least number of reflections.

To validate the algorithm developed in Matlab®, physical rays produced by a laser were projected on a cross section of the full-scale collector. The photographs of these experiments are shown in Fig. 10.

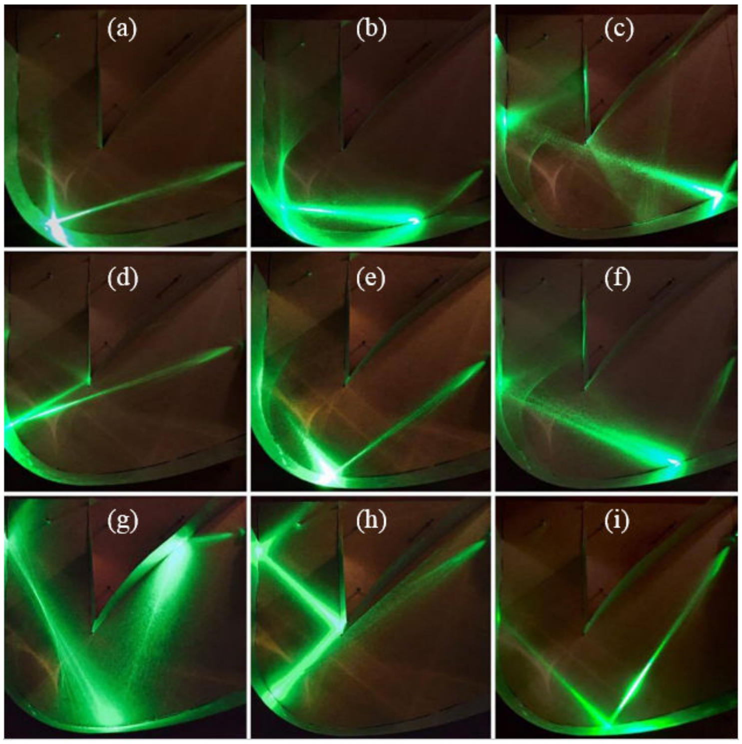

Fig. 10. Ray tracing using a laser for three solar altitude angles: 17º in (a), (d) and (g); 39º in (b), (e) and (h); 60º in (c), (f) and (i)

Comparing the predictions in Fig. 9 with the experiments in Fig. 10 validates the ray tracing algorithm a reliable technique for the optical design of the proposed solar collector.

4. Conclusion

The optimal geometry of the proposed solar air concentrator has been specified. The selection of an air heater IACPC collector with the absorber horizontally facing downwards aims to concentrate solar thermal energy inside the cavity and suppress heat losses. With the assistance of ray tracing, an optical analysis has been performed. A geometry has been determined that absorbs the highest amount of thermal energy with the minimum amount of reflective material. For future work, thermal analysis must be conducted along with optical modelling in order to characterise the tertiary section. With the physical manufacture of this solar concentrator, a comparison of the theoretical and actual results will be performed.

5. References

Alta D., Bilgili E., Ertekin C., Yaldiz O., Experimental Investigation of Three Different Solar Air Heaters: Energy and Exergy Analyses. Applied Energy, 2010; 87: 2953-2973.

Duffie J. A., Beckman W.A., Solar Engineering of Thermal Processes. 4th ed. Hoboken, New Jersey: John Wiley & Sons; 2013.

Eames P.C., Norton B., Kothdiwala A.F., The State of the Art in Modelling Line-Axis Concentrating Solar Energy Collectors. Newtownabbey: WREC, 1996.

Goswami D.Y., Principles of Solar Engineering. 3rd ed. New York: Taylor & Francis Group; 2015.

Mallick T.K., Eames P.C., Norton B., Power Losses in an Asymmetric Compound Parabolic Photovoltaic Concentrator. Solar Energy Materials and Solar Cells, 2007; 91: 1137-1146.

Rabl A., Comparison of Solar Concentrators. Solar Energy, 1976; 18(2): 93-111.

Shams N., Design of a Transpired Air Heating Solar Collector with an Inverted Perforated Absorber and Asymmetric Compound Parabolic Concentrator. PhD Thesis. Dublin: Dublin Institute of Technology, 2013.

Welford W.T., Winston R., High Collection Nonimaging Optics. San Diego: Academic Press, 1989.

Zacharopoulos A., Eames P.C., McLarnon D., Norton B., Linear Dielectric Non-Imaging Concentrating Covers for PV Integrated Building Facades. Solar Energy, 2000; 68(5): 439-452.