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Study of the influence of specularity on the efficiency of solar reflectors

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Abstract

One of the critical aspects characterizing the behavior of the solar mirrors is their specularity [1], which characterizes its capability to focus all the reflected light into the solar collector. Specularity is highly dependent on the roughness of the substrate used to manufacture the mirror, so the roughness of the substrate is definitely a key point to develop products of the highest optical quality with potential to substitute the conventional floated-glass mirrors.
A theoretical study taking into account the solar dispersion is developed to calculate the potential losses in parabolic through and power tower applications due to the use of non-completely specular mirrors.
Then, a study of the relationship between the roughness of the different surfaces and its specularity has been developed to determine whether they have the potential to be used as substrates for new generation reflectors with an optimum efficiency or not.
Besides, a study of the specularity of several commercially available mirrors is developed to determine its potential to be used in commercial solar plants. Finally, a 50 MW solar plant production case is developed for different reflector scenarios to estimate the production costs related to reflector losses in both solar concentrating technologies.

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Keywords: roughness; specularity; mirror; substrate;

1. Introduction

The need of increasing the efficiency of the solar plants to reduce the technology costs entails the study of different alternatives to improve the performance of the components. One of the components trying to be improved

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during the last years either by lower production price or improved efficiency is the reflector used in both, power tower and parabolic through plants, due to its high impact on the performance of the plants.

The second surface mirror manufactured with floated extraclear glass and silver as reflective layer is the common option used nowadays in the solar technologies. Its great durability and high optical efficiency makes it definitely a challenging opponent to beat. In the last years several designs have arisen in the market like polymeric film mirrors [2] or first surface PVD coated metal sheets.

Non-specular behavior of the solar reflectors can be given due to diverse factors as the scattering caused by dust accumulation on solar mirrors [3] or the use of a substrate which roughness causes deviation on the reflection of the light from the specular direction.

To determine the impact of the specularity on the efficiency of the solar collectors an experimental study has been developed. The superficial roughness of different samples has been characterized by means of a profilometer. Once its roughness is determined, it has been coated with a silver layer by means of sputtering PVD technique manufacturing a mirror. Then, the specular and hemispherical reflectance of the mirror is characterized, so the superficial roughness of the substrate and the specularity of the mirror relationship can be studied.

Besides, a theoretical study of the effective concentration ratio depending on the deviation produced on the mirrors reflection and a study of several commercial products, taking the results to economic terms has been developed.

Nomenclature

R_a	Surface roughness average or arithmetical mean roughness
R_q	Root mean square roughness
PDC	Pulsed DC, Pulsed Direct Current
sccm	Standard cubic centimetre per minute
FSM	Front Surface Mirror
DNI	Direct normal irradiance

2. Potential losses in solar plants due to use of non-completely specular reflectors

The concentrating efficiency of the solar reflectors used in the solar plants depends highly on the capacity of the mirrors to reflect the light in the specular direction without causing deviation [4]. Power tower and parabolic trough plants scenarios are studied in this section separately. In both cases the solar dispersion is taken into account in the model used to determine the impact of the potential deviation caused by the reflectors in the solar plants performance.

2.1. Solar dispersion

The solar dispersion due to the solar disk shape is included in the calculations presented in this section. The model used approximates the solar dispersion with a Gaussian function which dispersion is calculated through the mean distance of the sun to the earth and the diameter of the sun.

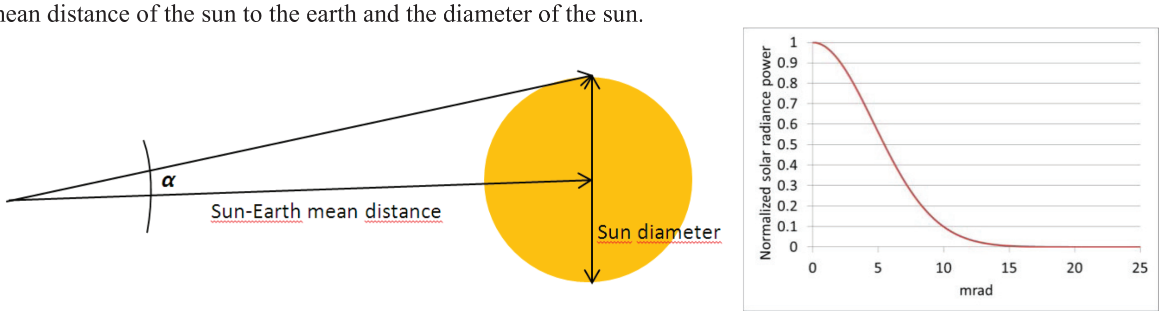

Fig. 1. Solar dispersion approximation by Gaussian function

Known the mean distance of the sun to the earth is 149.597.871 Km and the Sun diameter is 1.392.000 Km, the value of the half acceptance angle alpha is determined being its value of 4.65 mrad.

Thus, the sun Gaussian function is determined by a sigma equal to 4.65 mrad.

2.2. Parabolic through

For smooth surfaces, as the case studied, near-specular reflectance takes place, so the model radiance curves are represented by Gaussian functions. Thus, the reflected profile of the parabolic through collector can be represented by a Gaussian function which dispersion is calculated as a combination of the dispersions caused by solar profile and the reflector roughness:

$$\sigma_{eff} = \sqrt{\sigma_{sun}^2 + \sigma_{refl}^2} \tag{1}$$

In our model, we have geometrically determined the maximum deviation of the beams to be collected by the absorber tube of a parabolic through system which mirror´s aperture of 5.77 m and diameter of the absorber tube of 70 mm. Thus, the value of the maximum deviation is determined to be 20.47 mrad.

Known this value, the concentration ratio for parabolic trough systems as a function of the reflectance sigma is calculated as the ratio between the energy focused on the absorber tube (i.e desviation from specular direction is between 0 and 20.47 mrad) and the total energy reflected by the mirror, which is presented on figure 2.

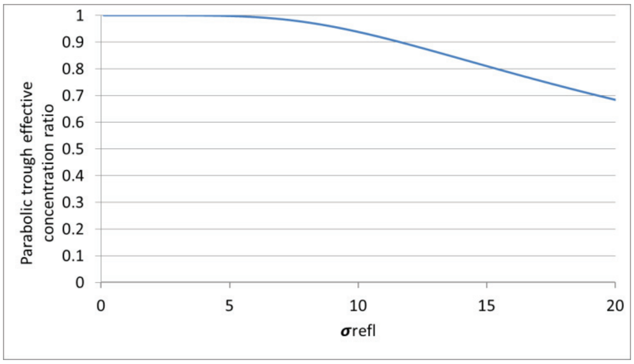

Fig. 2. Parabolic through effective concentration ratio

It can be highlighted that a concentration ratio of 0.9 is given for a reflectance sigma of 11.6 mrad.

2.3. Power tower

The case of power tower is much more sensible to deviations on the solar reflectors than for parabolic through. In the power tower receptors, the solar energy has to be distributed along the whole surface of the receiver pipelines, so minimal deviation on the mirror´s reflectance affects greatly the concentration ratio.

The case of a tower receptor with a double receptor of 45 m width each, forming a 45º angle respect to the plane normal to the mirrors and which height is 32 meters is evaluated for the concentration ratio of the farthest mirror, which is placed at 1200 m.

In our model, the mirror is shaped so the image of the sun covers the whole receptor with a spillage factor of 0.996, corresponding to the Gaussian function with a deviation mirror shape sigma of 7.11 mrad.

Then, we can obtain the concentration ratio in function of the deviation caused by the reflector through the equation 2.

$$\sigma_{eff} = \sqrt{\sigma_{sun}^2 + \sigma_{mirrorshape}^2 + \sigma_{refl}^2} \qquad (2)$$

The effective concentration ratio as a function of the deviation produced by the mirror is presented in figure 3.

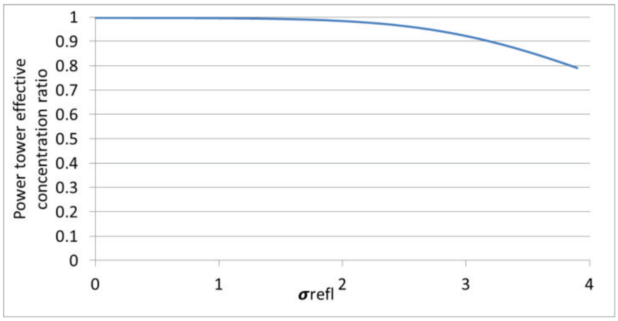

Fig. 3. Power tower effective concentration ratio

It can be highlighted that a concentration ratio of 0.9 corresponds to a reflectance sigma of 3.2 mrad.

3. Experimental study

3.1. Different substrates used to manufacturing a Front Surface Mirror

Eight substrates of Sst304 with different surface roughness were used in the study. Surface roughness of the samples was characterized by means of an optical imaging profilometer Sensofar Plμ2300. Ra and Rq roughness values were calculated according to the standard ISO4287 [5]. The values are shown in the table 1.

Table 1. Roughness of the samples

Samples	Ra (μm)	Rq (μm)
1	0.00319	0.0111
2	0.00623	0.0183
3	0.03	0.044
4	0.0852	0.116
5	0.102	0.131
6	0.598	0.756
7	0.716	0.902
8	1.34	1.81

The samples were coated by means of a silver sputtered layer of 120 nm. Silver was sputtered by means of a PDC cathode at 6kW, with an inlet flow rate of Argon of 200 sccm. Silver was chosen because it is known to be a great solar reflector material [6], protective layers as Al_2O_3 [7] or other weren´t included because the roughness influence on the reflectance was the only parameter of interest in the study and a durable FSM was not intended to be manufactured.

Once the FSM were prepared, the total or hemispherical reflectance of the sample and the specular reflectance (i.e half acceptance angle 30 mrad) on the whole solar spectrum (300-2500 nm) were characterized by means of a spectrophotometer designed and manufactured in the Photonics Technology Group at the University of Zaragoza.
The results of the measurements are shown in figures 4 to 7.

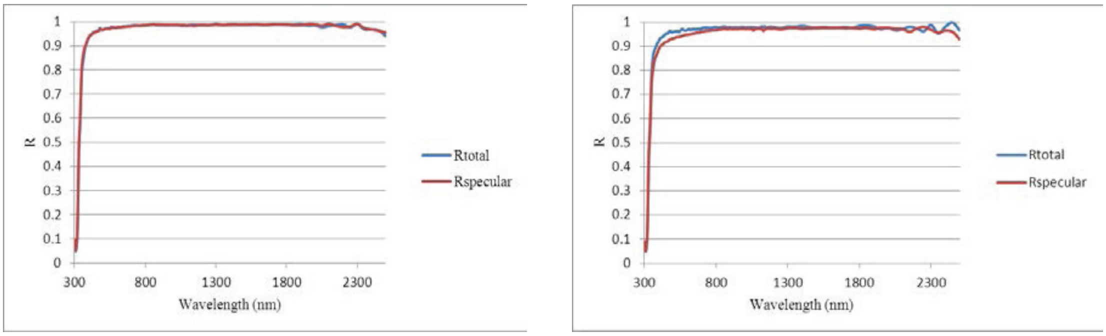

Fig. 4. (a) Ra = 0.00319 μm/ Rq = 0.0111 μm; (b) Ra = 0.00623 μm/ Rq = 0.0183 μm.

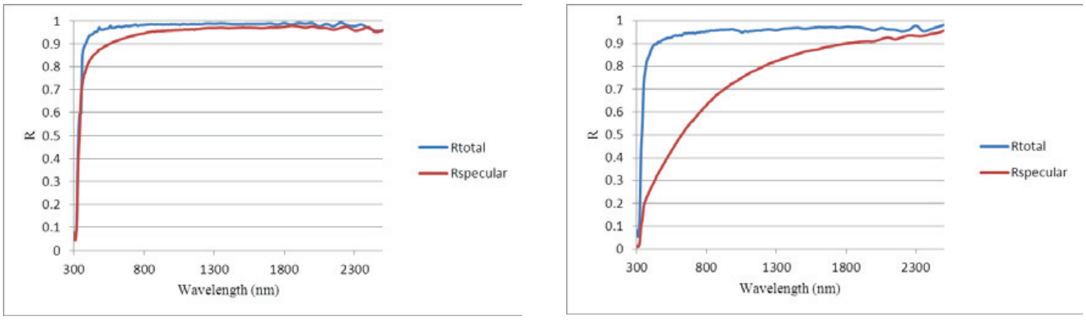

Fig. 5. (a) Ra = 0.03 μm and Rq = 0.044 μm; (b) Ra = 0.0852 μm and Rq = 0.116μm.

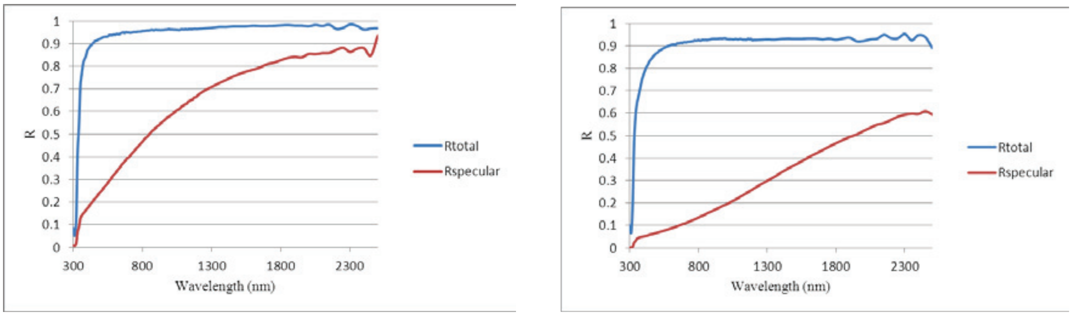

Fig. 6. (a) Ra = 0.102 μm/Rq =0.131 μm; (b) Ra = 0.598 μm/ Rq = 0.756μm.

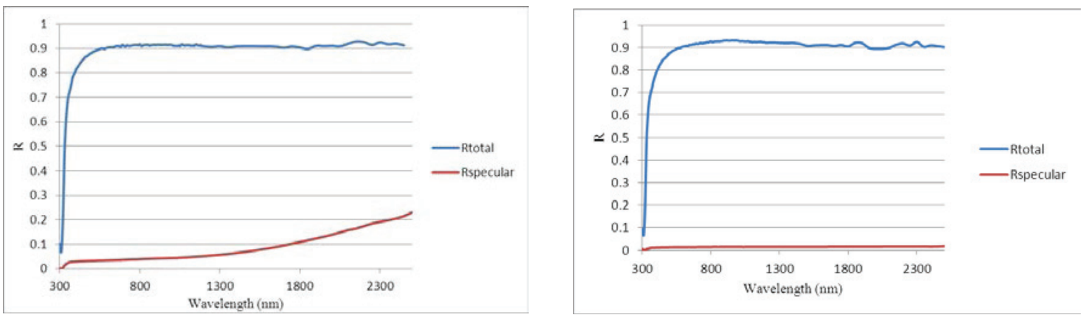

Fig. 7. (a) Ra = 0.716 μm/Rq =0.902; (b) Ra = 1.34 μm/ Rq = 1.81μm.

The solar weighted reflectance was calculated according to ASTM G173 [8]for both, specular and total reflectance. The values calculated are shown in table 2.

Table 2. Solar weigthed reflectances according to ASTM G173

Roughness (Ra) (μm)	Total R	Specular R
0.00319	96.9%	96.9%
0.00623	96.6%	94.6%
0.03	96.5%	91.6%
0.0852	93.9%	57.6%
0.102	93.8%	44.7%
0.598	89.5%	16.2%
0.716	89.1%	4.5%
1.34	89.0%	1.4%

It can be observed that the only substrate which presents an completely specular behaviour is the one which surface roughness is 0.00319 μm. The rest presents only partial specular behaviour. It is clear that the bigger the roughness of the substrate the bigger diffusion is produced in the light reflexion, so a less specular behaviour is produced by the mirrors manufactured as its surface roughness increases. This can be observed in figure 8.

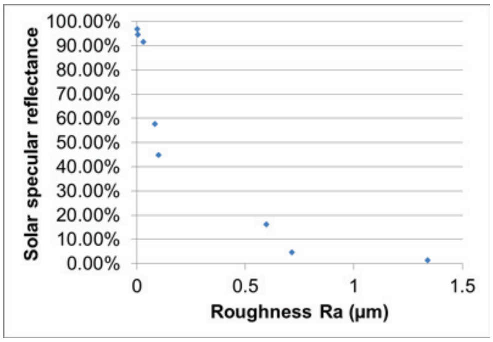

Fig. 8. Specular solar reflectance.

Besides, it is remarkable the decrease of the total solar reflectance that is produced as the roughness of the substrate is increased. This effect is caused, possibly, due to the multiple reflection phenomena taking part on rougher surfaces before being reflected outside the sample. This effect is represented in figure 9.

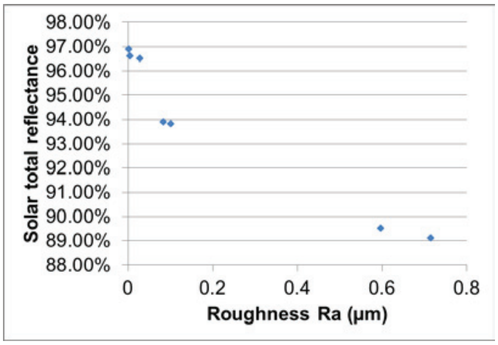

Fig. 9. Total solar reflectance.

This decrease of the total reflectance is especially significant for different applications than the ones studied in this paper, as secondary concentrators for concentrated photovoltaic or others. In some of these applications the specularity is not so critical to achieve proper focalization of the solar energy. Anyway, the decrease of the total reflectance affects strongly the efficiency of the solar reflectors. Thus, the roughness of the substrate is a key feature to develop high quality mirrors also in cases where complete specularity maybe is not critical, but the total reflectance needs to be maximized.

3.2. Commercial products characterization

Four different commercial mirrors were optically characterized , measuring the total and the specular reflectance. Besides, a floated glass second surface commercial mirror was characterized as well to be used as a reference for the comparation of the optical properties.
First, two FSM with metallic substrates were characterized. The results are shown on figure 10, including the characterization of the floated glass mirror.

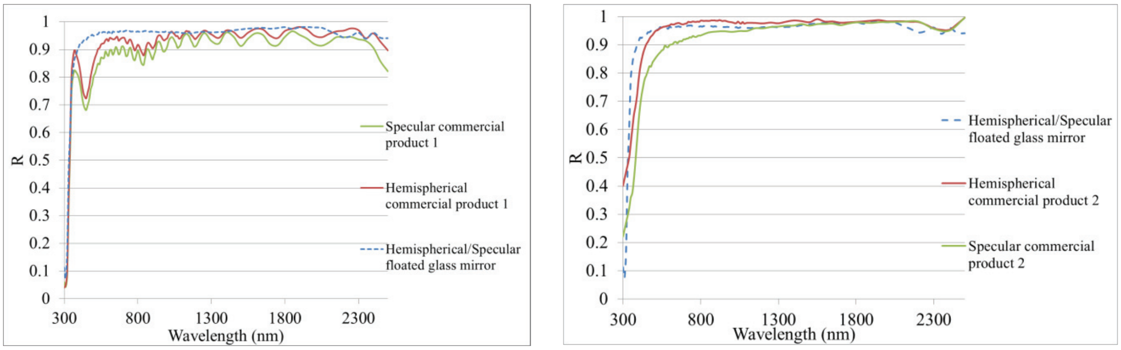

Fig 10. (a) Commercial product 1 vs floated glass mirror (b) Commercial product 2 vs floated glass mirror

Is interesting to point the interference produced by the protective layers in the commercial product number 1. This interference is clearly observed in the wavy form of the reflectance spectrum. The highest losses in this product, compared to the floated glass mirror takes place in the visible part of the spectrum. The second commercial product presents a high total reflectance, but the specular reflectance is quite lower in the ultraviolet, visible and start of the nea infrared spectrum, which decreases its potential performance for thermosolar applications.

Besides, two polymeric commercial mirrors were characterized. The results are shown on figure 11, including the characterization of the floated glass mirror.

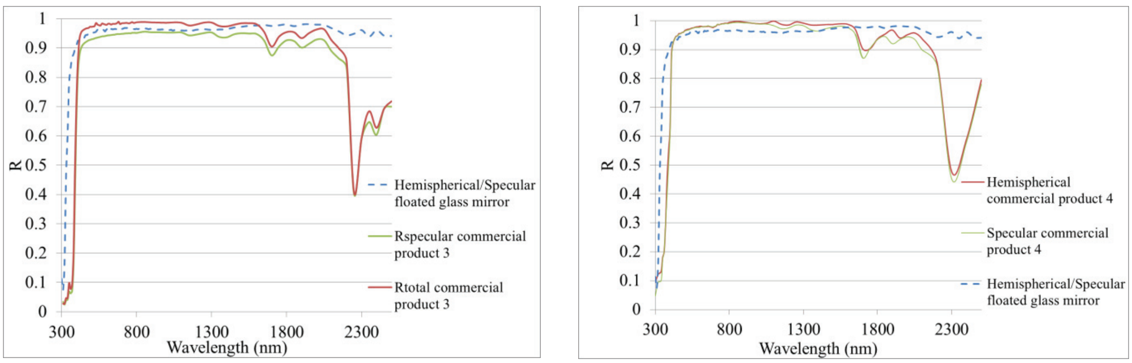

Fig. 11. (a) Commercial product 3 vs floated glass mirror (b) Commercial product 4 vs floated glass mirror

For the polymeric products studied, it should be pointed out the high specular reflectance obtained in product 4 on the visible and start of the near infrared spectrum. However, the losses produced by absorption of the polymer in the ultraviolet and end of the near infrared spectrum impacts highly on the solar weighted reflectance values. Thus, these products presents higher specular reflectance that commercial products number 1 and 2, but its optical performances for thermosolar technology is quite lower than the one of the floated glass second surface mirror.

The total and the specular solar reflectance of the four commercial products and the floated glass second surface mirror are shown on table 3.

Table 3. Solar weigthed reflectances according to ASTM G173

Product	Total R	Specular R
Commercial product 1	90.4%	86.7%
Commercial product 2	94.8%	88.0%
Commercial product 3	93.6%	89.9%
Commercial product 4	93.1%	92.1%
Floated glass mirror	95.1%	95.1%

It is interesting to highlight the biggest specular reflectance of the commercial products characterized is the one of the second surface floated glass mirror. This optimum optical performance makes it, nowadays, the standard product used in the solar market.

4. Thermosolar plants of 50 MW case study

Two cases studies are analyzed in this section. A parabolic through and a power tower plant, both of 50 MW are considered. The oversizing needed in the plants, due to the use of non-completely specular mirrors is determined, and the diminution in costs of the affected elements of the plants to be cost competitive with the floated glass option is discussed.

4.1. Power tower case

A standard 50 MW power tower plant uses, approximately, 3640 heliostats of 121 m^2 to concentrate the solar energy on the receiver for the needed production.

The lower performance of the four commercial products respect to the floated glass mirrors makes necessary the oversizing of the heliostats field to match the proposed production. Thus, the percentage of extra heliostats needed if one of these products were chosen is calculated. This data is shown in table 4.

Table 4. Solar specular reflectances and number of heliostats for 50 MW power tower plant

Product	Specular R	Number of heliostats for 50MW plant	Percentage of extra heliostats needed
Commercial product 1	86.7%	3991	7.2%
Commercial product 2	88.0%	3933	8.0%
Commercial product 3	89.9%	3849	5.7%
Commercial product 4	92.1%	3758	3.2%
Floated glass mirror	95.1%	3640	

The price diminution of the alternative heliostats (including the structure, tracking system and mirrors) needed to equal the cost of a floated glass mirror plant has been calculated and is shown in table 5.

Table 5. Price respect to floated glass heliostat to be price competitive

Product heliostat	Price to be competitive with floated glass
Commercial product 1	91.2%
Commercial product 2	92.5%
Commercial product 3	94.6%
Commercial product 4	96.8%

A large diminution on the prices of the heliostats would be needed to be cost competitive using another product than floated glass mirror. The best performance of the glass mirror makes it, clearly, the best option.

4.2. Parabolic through case

If the commercial products studied were used in a parabolic through plant, as the specular solar reflectance is lower than that of the floated mirror glass, more meters of the collector system would need to be added to every loop of the 50MW plant to achieve the same performance.

Simulations were run by means of Abengoa Solar´s R&D production software, in a standard 50 MW case where the DNI considered was 1000 W/m^2, to calculate how many meters are needed for every commercial product option to achieve the same output fluid temperature than using the floated glass mirror option in a common plant configuration. The results are exposed in table 6.

Table 6. Solar specular reflectances and number of meters needed per loop for 50 MW power tower plant

Product	Specular R	Loop meters needed	Percentage of extra meters needed
Commercial product 1	86.7%	646	10.4%
Commercial product 2	88.0%	633	8.2%
Commercial product 3	89.9%	621	6.1%
Commercial product 4	92.1%	605	3.4%
Floated glass mirror	95.1%	585	

Finally, the price per meter of the whole solar loop (including tube receiver, tracking system, collector structure and mirrors) corresponding to the four studied products respect to a floated glass conventional loop to equal its cost should be much lower as is exposed in table 7.

Table 7. Price respect to floated glass per meter of PT to be price competitive

Product heliostat	Price to be competitive with floated glass
Commercial product 1	90.5%
Commercial product 2	92.4%
Commercial product 3	94.2%
Commercial product 4	96.6%

A large diminution on the prices of the whole loop system would be needed to be cost competitive using another product than floated glass mirror. The best performance of the glass mirror makes it, clearly, the best option.

5. Conclusions

- The specularity of the reflectors impacts directly on the production of the thermosolar technologies, either in power tower and parabolic trough plants. Highly specular mirrors are needed so the production is not affected.
- Commercial products should clearly specify solar weighted specular reflectance values in order to be valued properly for thermosolar applications.
- Specular reflectance depends strongly on the substrate roughness, decreasing dramatically as the roughness of the surface is increased.
- Total reflectance depends also on the surface roughness, possibly due to multiple reflections on the mirror surface.
- Four commercial products were evaluated against a floated glass mirror. The best optical performance was achieved by the floated glass mirror which presents a completely specular behavior and the highest solar weighted specular reflectance.

Acknowledgements

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