Technical and Economic Feasibility Study of the application of anodized aluminum sheets in the solar field of Heliothermal Power Plants

https://doi.org/10.56238/sevened2024.018-054

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ABSTRACT

The work analyzes the technical economic feasibility of the application of anodized aluminum sheets, instead of glass mirrors, in the solar field of parabolic cylinder heliothermal plants. The adaptation of this technology to the Brazilian case is evaluated. From the qualitative analysis of the technical specifications of the two types of reflectors, and the simulations carried out in the SAM, it is possible to conclude that systems with glass reflectors have better properties than aluminum mirrors, however, from the economic point of view, aluminum mirrors would allow to achieve economic viability for projects that operate in medium temperature ranges.

Keywords: Heliothermic, Solar concentration, Parabolic cylinder, Anodized aluminum reflector, Glass mirror reflector.

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INTRODUCTION

Heliothermal technology is capable of generating energy in the form of heat and electricity through the transformation of direct solar irradiation (DNI). Presenting advantages over other renewable energy sources, such as wind and solar photovoltaic, solar thermal generation is flexible and capable of being dispatched (13).

Due to their ability to store energy in the form of heat, to generate electricity and process heat, including for cogeneration, and to be hybridized with several other energy sources, solar thermal plants usually have a higher capacity factor than other renewables, being able to operate on the basis with firm energy, as well as meet peak loads and demand for ancillary services at any time of the day (1); (4); (12).

As highlighted in the Brazilian Electric Sector Expansion Plan (8), alternatives have been sought to meet peak and demand fluctuations that ensure the safety and stability of the system, but that also contribute to low tariffs and the reduction of greenhouse gas emissions. Such characteristics, added to the fact that Brazil has a great potential for solar thermal generation due to the high incidence of DNI, has made solar thermal technology very attractive to the Brazilian electricity sector.

However, there are still some challenges regarding this source, especially with regard to its economic viability. According to the Renewable Cost Database study (6), CSP projects have been showing a downward trajectory of levelized energy costs. However, this technology is still significantly more expensive than other renewable sources, such as solar photovoltaic and onshore wind, and far from being considered commercial. With this objective, several countries have been seeking new concepts of solar thermal generation that make it possible to lower the cost of the production process of their components and increase their productivity.

In this context, in 2015, ANEEL held the Call for Strategic R&D Project No. 019/2015 "Development of National Technology for Heliothermal Generation of Electricity" with the objective of studying the possibility of producing components of solar thermal plants in Brazil and stimulating the scientific and technological development of this energy source in Brazil, in which the authors of the article participate.

According to data from NREL (10), the solar field was the component with the largest share (31%) in the investment cost of a CSP parabolic cylinder plant with heat storage. An alternative to lower the cost of the solar field is the replacement of borosilicate glass mirrors with anodized aluminum plates. Despite resulting in a slight drop in efficiency and lower durability due to inclement weather, the use of aluminum reflectors in solar thermal plants is significantly cheaper, less complex to produce and easier to transport.

In addition, the production of solar fields for solar thermal generation in Brazil could be a way to promote the opening of a new market for the national aluminum industry, which has been suffering from the high price of electricity and competition with Chinese products.

Thus, this work aims to make a qualitative analysis of parameters that can impact the technical economic feasibility of the application of anodized aluminum sheets, instead of borosilicate glass mirrors, in the solar field of solar thermal plants and to evaluate the adaptation of this technology to the Brazilian case, especially for smaller installations that are also suitable for cogeneration applications in industrial processes.

REFLECTOR MATERIALS AND THEIR CONFIGURATIONS

In this topic, the theoretical references for heliothermal reflector materials and their configurations will be addressed, in order to support the methodology of the work. Collectors for solar concentration require the use of selective surfaces with high specular reflectance of the solar spectrum. Reflective metals typically used in solar reflectors are silver and aluminum, due to the good reflective properties in the spectral range of sunlight incident on Earth. The reflectance of silver is considerably higher than that of aluminum for most wavelengths (>500 nm). The solar hemispherical reflection of silvery surfaces can reach a maximum of 98% in a vacuum, while for aluminum the maximum is 92% (3).

The configurations of a solar reflector are usually based on highly bright metals or metallic coatings placed on substrates such as glass, polymers or metals. When the substrate is opaque, the reflective layer should always be the front surface, e.g. with polished aluminum. In this case, the reflector is known as the "front surface" or "first surface". These reflectors, to improve durability, can have a very thin and transparent front coating (<5 µm thick). On the other hand, if a transparent substrate (glass, methacrylate, polycarbonate) is used, the reflective coating should be on the back surface of the substrate, being known as a "second surface" reflector. Both metals require high-quality protective coatings to protect against corrosion. First surface mirrors require clear coatings on top. Second-surface reflectors always have protective coatings behind them (varnish), or are bonded to additional substrates.

The characterization made in the following is a synthesis of Chapter 3 of Heller's book (3), on materials and configurations of reflectors for solar concentration.

SECOND SURFACE REFLECTORS

Thick glass silver mirrors

It is composed of a layer of reflective silver coated on the front surface by a thick layer (3-4 mm) of monolithic glass. Given that glass can have a low content (0.02%) of Fe_2O_3, which absorbs a portion of solar irradiation, the type of glass used for the solar industry is called "light white" or low-iron glass. The silver layer (with an average density of 0.8 -1.2 g/m2) is extremely vulnerable to ambient contaminants, humidity or salty atmosphere. Therefore, in addition to front protection, protection from behind is also important. This protection is achieved with one layer of copper, and two or three layers of protective coating paint that contains some lead (0.5% to 2.5% by weight).

In the process of manufacturing the mirror with thick curved glass, the flat glass is heated in furnaces over a parabolic mold; Then, the glass is silvered on the back surface. Finally, the silver surface on the back is covered with the coatings.

A high reflectance is achieved due to the intrinsic properties of silver, and may have little scattering due to the fact that glass is a very smooth substrate.

Thin glass silver mirrors

The configuration is very similar to the thick glass mirror, the main difference is the thickness of the glass layer, less than 1 mm. To obtain the shape of the collector and give the collector robustness, the reflectors are glued to the metal, polymer or composite material structures. The reflectance is even higher than the thick glass reflector because the top glass layer is thinner, and as a consequence, the optical path of the sun's rays is smaller. These reflectors are lighter and cheaper than thick glass ones, but the cost of the back frame must be added.

Silver Laminated Glass Mirrors

These reflectors use silver as a reflective layer, protected by a layer of glass on both sides, front and back, similar to the windshields in cars. The reflectance is similar to the thin glass reflector, because the front layer of glass is typically between 1 to 2 mm thick. The total thickness of the reflector is similar to that of the thick glass reflector. The shape is given during the thermal manufacturing process. The resistance and durability of this mirror are greater than the previous ones, but the production cost is higher.

FIRST SURFACE REFLECTORS

Anodized Aluminum Mirror

Depending on the top coating, various aluminum reflectors are available. The best known is built with pure aluminum deposition on a polished aluminum substrate with a layer of aluminum oxide between the two (anodized) and some clear coatings on top. For example, with a layer of alumina ($SiO2$), which is useful for protecting against abrasion and corrosion. Other reflectors use organic coatings or anodized aluminum as the top layer.

Aluminum reflectors are increasingly used for solar concentrating applications due to their low weight, high ductility (they withstand wind loads without damage), and flexibility in design, construction, and assembly. The manufacturing process also allows for massive production: the coiling process. As a result, these reflectors have the potential for cost savings compared to glass mirrors.

On the other hand, in addition to the low reflectance of aluminum, the marks of the coiling process generate a rougher surface than that of glass mirrors, which leads to greater scattering of solar irradiation. The lower reflectance of aluminum compared to silver makes aluminum reflectors more appropriate for industrial process heat generation (SHIP) applications, and not as appropriate for electrical generation (CSP). In addition, the duration of these reflectors in urban, industrial and polluted environments is shorter than those of silver. To increase the duration, flat glass covers can be added to the aperture plane in small parabolic cylinders.

Silver Polymer Film Mirrors

These mirrors use a silver reflective layer protected on the front by several layers of polymers, and deposited on a substrate (usually it is also a polymer). The polymer substrate limits the temperature (60-80°C) during silver deposition. This material is lightweight and flexible, so it is easy to adapt it to the parabolic collector. The process of bonding the silver film to the substrate (glass, methacrylate, polycarbonate) must be done with great care to prevent bubbles from getting trapped, which can deflect the reflected rays.

METHODOLOGY

The comparison between the two types of solar field (glass mirror and aluminum mirror) will be made, at first, through the qualitative analysis of the technical specifications of two types of commercial parabolic cylinder collectors. Two types of parabolic cylinder manifolds were chosen (Table 1 and Figure 1):

a) large collectors with reflective surface of glass mirror, Solargenix brand, and Schott PTR-70 receiver;
b) small collectors, with anodized aluminum surface, and receiver, both from the Mexican brand Inventive Power.

In a second moment, the System Advisor Model (SAM) software was used to simulate the operation of solar concentration projects in Brazil, in Bom Jesús de Lapa – NE, using the two types of systems described above (using the properties presented in table 1).

For the second part, the simulation of projects using the two types of collectors, the System Advisor Model (SAM) software was used. SAM is a free-to-use software, developed by the National Renewable Energy Laboratory (NREL). SAM was chosen because of the versatility it presents through its module for evaluating process heat generation projects with solar concentrators. It is noteworthy that in order to meet the objectives of the work, to analyze the technical and economic feasibility of projects with glass or aluminum mirrors, only the generation of heat in the solar field was simulated. Electrical generation was not simulated, which would be possible by harnessing the heat generated in the solar field in a power block, after heat exchange between the thermal fluid circulating through the solar field and the working fluid. Several authors have already used the SAM model for several research works in the area of CSP in Brazil, for example: in the evaluation of CSP plants hybridized with biomass in the Brazilian Northeast (14).

FIGURE 1 - Commercial parabolic cylinder manifolds.

(a) Large collectors with Solargenix glass mirror reflective surface and Schott PTR-70 receiver. (b) anodized aluminum surface collectors and receiver, Inventive Power brand.

The SAM model is able to integrate the financing, incentives, costs and performance of a solar concentration plant within a single model, enabling a consistent analysis for good decision-making, looking at both technological and financial issues (15); (9).

In addition, SAM has the ability to use a variety of climatological data in various formats (TMY3, TMY2, EPW), which gather the necessary information (DNI, wind speed and ambient temperature) for the design of the solar field and for the calculation of the energy generated over a typical year at one-hour intervals (11).

The data presented in Table 1 were used to configure the two simulated solar concentration systems: a) large-scale, with collectors that have glass mirror reflectors, and b) small-scale, with collectors that have aluminum reflectors. The capital costs, fixed and variable O&M, presented in Table 2, were also considered.

Soria et al. (14) communicated directly with the Canadian company Naanovo Company, which expressed interest in participating in the Brazilian market to develop CSP projects. The company indicated that by using SolarMaax anodized aluminum collectors and smaller Schott receivers, and installing an assembly plant in the Northeast region, it would be possible to achieve a capital cost of 10% to 20% lower than typical designs based on glass mirror reflectors. This hypothesis is justified by technological learning at the global level in the period 2020 – 2025 (2); (5); (7), but also to the reduction of import and transport costs to the project sites.

Table 1. Comparison of the technical specifications of parabolic cylinder manifolds with glass mirror and with aluminum mirror.

General Features and Technical Specifications of Parabolic Cylinder Manifolds			**Unit**	**Large-scale projects, glass collectors**	**Small-scale projects, aluminum collectors**
General features		Temperature range - solar heat for industrial processes	°C	90-260	45-130
		Lifespan	Years	40	>20
Collector	Collector geometry	Collector		Solargenix SGX-1	Inventive Power - PT 110 ®
		Reflective surface		Glass mirror	Anodized aluminum - reflective blade ALANOD Miro Sun
		Reflective surface opening area	m2	470,3	3,09
		Full width of reflective surface with structure	m	5	1,21
		Length of a collector	m	8,33	3,05
		Average distance between reflective surface and focus	m	1,8	0,341
		Average Pipe Distance Between Assemblies	m	1	1
	Optical Parameters	Tracking error		0,994	0,988
		Geometry Effects		0,98	0,952
		Reflective surface reflectance		0,935	0,90
		Reflective surface dirt		0,97	0,97
		General optical error		0,99	1
	Optical collector calculations	IAM on the summer solstice		1,00361	0,999903
		Final loss on the summer solstice		0,999752	0,994658
		Optical efficiency in design		0,874643	0,821123
Receptor	Receiver geometry	Receptor		Schott PTR70	Inventive Power -PT 110
		Inner diameter of absorber tube	m	0,066	0,030

		Outer diameter of the absorber tube	m	0,07	0,033
		Inner diameter of glass envelope	m	0,115	0,0656
		Outer diameter of glass envelope	m	0,125	0,07
		Material Type of Glass Envelope		Borossilicate	Borossilicate
		Absorber flow plug diameter	m	0	0
		Roughness of the inner surface		4,5*10^-5	4,5*10^-5
		Type of absorbent material		AISI 304L	AISI 304
	Receiver: parameters and variations	Absorber absorption, selectively coated		0,96	0.87 (Solkote coating)
		Absorber emittance, with selective coating		0,095	0.35 (Solkote coating)
		Glass envelope emittance		0,86	0,85
		Transmittance of glass envelope		0,97	0,92
		Glass coating		Anti-reflective	n.a.
	Receptor: Total weighted losses	Optical reduction		0,869751	0,733407
		Heat loss at the design point	W/m	190	n.a.

Source: prepared by the authors from (13), (14) and (15).

Table 2. Capital costs, fixed and variable O&M costs, for simulated systems.

Material	**Cost of capital (USD/kW-t)**	**O&M fixo (USD/kW)**	**Variable O&M (USD/kWh-t)**
With glass mirror	560	8	0,001
With anodized aluminum	500-400	7	0,001

Source: prepared by the authors from (13), (14) and (15).

Table 3. Results for comparison between glass and aluminum mirror.

Material	**Average Efficiency (%)**	**Surface-to-installed power ratio (Wt/m2)**	**Reduction in LCOH**	**Local content in the project (%)**
With glass mirror	61	150	Reference	Medium
With anodized aluminum	48	90	7% to 12%	High

Source: prepared by the authors from (13), (14) and (15).

The System Advisor Model (SAM) integrates financing, incentives, costs and performance of a solar concentration plant into a single model, allowing for consistent analysis for decision making, addressing both technological and financial aspects.

In addition, SAM can use various climatological data in various formats (TMY3, TMY2, EPW), which include essential information such as DNI, wind speed and ambient temperature. This data is crucial for solar field design and for calculating the energy generated over the course of a typical year at hourly intervals.

Thus, the data in Table 1 were used to set up two simulated solar concentration systems on glass and anodized aluminum mirror reflectors. Capital costs and fixed and variable O&M were also considered, as shown in Table 2. And from these constructions, it was possible to establish project comparisons between the two technologies.

RESULTS AND DISCUSSIONS

From the qualitative analysis of the technical specifications of the two types of reflectors, and from the simulations carried out at SAM, it is evident that systems with glass reflectors have better properties than aluminum mirrors. However, from the economic point of view, aluminum mirrors would allow economic viability to be achieved in some projects, as shown in Table 3.

The glass mirror due to better reflectance, lower optical error, better optical efficiency, larger size of each collector unit and longer life time, is suitable for large-scale projects of high-temperature industrial process electric or heat generation (90 – 260°C). On the other hand, glass mirror collectors have a higher cost of capital, which makes it difficult to access financing, as well as the expense of interest payments will be higher, and finally, leads to a more expensive final energy. Thus, it is recommended to use this technology for large projects that demand higher working temperatures, and where the value of the land is high and it makes sense to install high-efficiency systems, given that these require a smaller installed area to generate the same amount of energy.

Glass mirror collectors also have a longer service life. Much research, however, has focused on techniques to improve the design and technical characteristics of aluminum reflectors. For example, the development of more sophisticated coatings for aluminum would make it possible to extend the life of the system.

Given that they have a smaller solar capture surface and consequently greater modularity, projects that consider aluminum mirrors are appropriate for smaller projects that operate in an average temperature range (45–130°C), being ideal for heat generation for industrial processes, for example.

On the other hand, systems with aluminum mirrors need a larger capture area per unit of installed capacity to compensate for their lower optical and energy conversion efficiency. However, despite their lower efficiency, due to the low capital cost, the levelized cost of heat in designs based on aluminum reflectors tends to be 7 to 12% lower compared to designs that use glass mirrors (Table 3).

It is worth remembering, however, that this difference in levelized cost can be changed if financing is considered for the project. Due to the lower capital cost of solar thermal plants with aluminum mirrors, they have easy access to financing lines. Plants with aluminum mirrors, due to their size, can be adapted to strategic financing lines with more attractive rates.

In the simulated case, the lower efficiency of the collector with an aluminum reflective surface must also be explained by the thermal properties of the receiver: lower absorptivity of the receiving tube, lower transmittance of the glass envelope, lower optical efficiency, etc.

CONCLUSION

The qualitative and quantitative analysis of the technical specifications of the parabolic cylinder manifolds with glass and aluminum reflectors, complemented by the simulations in the System Advisor Model (SAM), revealed important insights into the technical and economic feasibility of each system. Glass reflectors stand out for their better optical properties, lower optical error, greater efficiency and durability, being more suitable for large projects that demand high operating temperatures. In contrast, aluminum reflectors, despite having lower efficiency and greater need for catchment area, are economically viable in certain projects due to the lower cost of capital.

Glass collectors, with their high reflectance and optical efficiency, are ideal for large-scale projects aimed at generating electricity or heat from high-temperature industrial process (90 – 260°C). However, the high cost of capital and the difficulties associated with financing make these systems less affordable, increasing the final cost of the energy generated. The longer life of glass collectors also justifies their use in projects where durability and long-term efficiency are crucial.

On the other hand, aluminum collectors, with lower initial costs and greater modularity, are more suitable for smaller, medium-temperature (45 – 130°C) projects, such as heat generation for industrial processes. Despite its lower efficiency, the levelized cost of heat in designs with aluminum reflectors tends to be 7 to 12% lower compared to designs with glass mirrors. This factor, combined with easier access to financing lines due to the lower cost of capital, makes aluminum collectors an attractive option for certain projects.

The lower efficiency of aluminum collectors can be attributed not only to their optical characteristics, but also to the thermal properties of the receiver, such as lower absorbency of the receiving tube and lower transmittance of the glass envelope. This underscores the need for improvements in the design and technology of these systems to increase their competitiveness.

As a recommendation for future studies, investments in various parts and components of the solar thermal plant can be cited. As an example, the following developments can be cited:

- Advanced Coatings for Aluminum Reflectors, in which research should focus on the development of coatings that increase the durability and efficiency of aluminum reflectors, enabling greater competitiveness against glass mirrors.
- Thermal Receiver Optimization: Improvements in the thermal properties of the receivers, such as increased absorptivity and transmittance, can increase the overall efficiency of aluminum reflector systems.
- Cost-Benefit Analysis with Different Financing Scenarios: Studying the impact of different financing conditions on the economic viability of projects can provide valuable

insights for investors and policymakers.

Thus, investment in research and development is encouraged through real case studies, with the implementation and monitoring of pilot projects, using both types of collectors, which can provide essential empirical data to validate the theoretical and simulation conclusions of this work.

In this way, it is expected not only to enhance existing technology but also to expand the efficient use of concentrated solar energy in different contexts and scales, thus contributing to global energy sustainability.

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