PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE

ESCUELA DE INGENIERÍA

SOILING EFFECT ON REFLECTIVE MIRRORS OF CONCENTRATING SOLAR PLANTS UNDER CHILEAN CLIMATIC CONDITIONS

NATALIA MARÍA BUGEDO CAROCA

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Advisor:
RODRIGO ESCOBAR M.

Santiago de Chile, August, 2016.

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Members of the Committee:

RODRIGO ESCOBAR M.

AMADOR GUZMÁN C.

ALAN PINO A.

GONZALO CORTÁZAR S.

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RESUMEN

Las plantas solares de concentración térmica utilizan espejos para reflejar la radiación solar sobre un receptor térmico. El ensuciamiento disminuye la reflectancia de los espejosy por ende disminuye la producción térmica de la planta.

La medición de la tasa de ensuciamiento es un proceso fundamental en el desarrollo de una planta solar de concentración ya que aporta en las estimación de producción por ser un input influyente en la producción energética.

En este trabajo se estudia el efecto del ensuciamiento en espejos refletores. Se realizan pruebas de exposición para medir valores de disminución de reflectancia diaria para dos materiales distintos en las afueras de San Felipe en la Región de Valparaíso, Chile. Luego, se propone un modelo económico para obtener el ciclo óptimo de limpieza de los espejos considerando una reflectancia objetivo anual.

La tasa de ensucimianto promedio diaria encontrada para los materiales estudiados fue de 2,14% para las láminas poliméricas y de 1,16% para las muestras de vidrio monolítico. La diferencia en sus tasa de ensuciamiento indica que para mantener una misma reflectancia anual, las láminas poliméricas deben compensar con una mayor frecuencia de limpieza o disminuyendo su producción energética.

Para el modelo económico propuesto, se utilizaron los valores de ensuciamiento medidos en las pruebas en terreno. Los resultados entregan costos y frecuencias para distintos tamaños de plantas solares de concentración. Para plantas pequeñas se utilizan métodos manuales de limpieza, sin embargo cuando las plantas ya superan los 10.000 m^2 de superficie reflectora de los espejos es conveniente usar metodos automatizados como los camiones de limpieza.

En conclusión, el ensuciamiento en las plantas solares es un problema que afecta la producción energética y la contabilidad del proyecto. Es importante tener mediciones locales y estacionales de la tasa de ensuciamiento para así hacer modelaciones reales de cual es el ciclo óptimo de limpieza y no tener gastos excesivos.

ABSTRACT

Solar thermal plants use mirrors to reflect solar radiation on a thermal receiver. These mirrors have reflective features that ensure high performance of the plant. However, soiling decreases their reflectance and thus decreases the thermal output of the plant.

Measuring the soiling rate is a fundamental process in the development of a solar concentration plant since it provides information for the estimations of energy production.

In this paper the effect of soiling in refletores mirrors is studied. A exposure test is conducted for measuring the drecrease in daily reflectance for two different materiales in the countryside of San Felipe in the Valparaíso Region, Chile. An economic model is then proposed to obtain the optimal cleaning cycle of the mirrors considering an annual reflectance target.

The average daily soiling rate for the materials studied was 2.14% for polymer films and 1.16% for samples of monolithic glass. These two materials used in the solar industry have similar reflective properties but the polymer films are cheaper, lighter and more flexible. The difference in their soiling rate indicates that to maintain a same annual reflectance, the polymer sheets must compensate a higher cleaning frequency or decreasing its energy production.

For the proposed economic model, soiling values measured in field tests were used. The results gave cost and frequencies for different sizes of solar concentration plants. For small plants manual cleaning methods are used, however when plants are bigfger than 10,000 m2 of reflective mirror surface it is convenient to use automated methods such as cleaning trucks.

In conclusion, soiling in solar mirrors is a problem affecting energy production and project accounting. It is important to have local and seasonal measurements of the soiling rate in order to make real modeling of which is the optimal cleaning cycle and not having overspending.

1 INTRODUCTION

1.1 Motivation

Global warming is an international issue and this is because of the increase in greenhouse gases (GHG) in the environment. One of the main reasons for GHG increase is the high usage of fossil fuels, which are the main base for energy production in the world. More than 60% of primary energy and final consumption depends on fossil fuels as displayed in Figure 1-1.

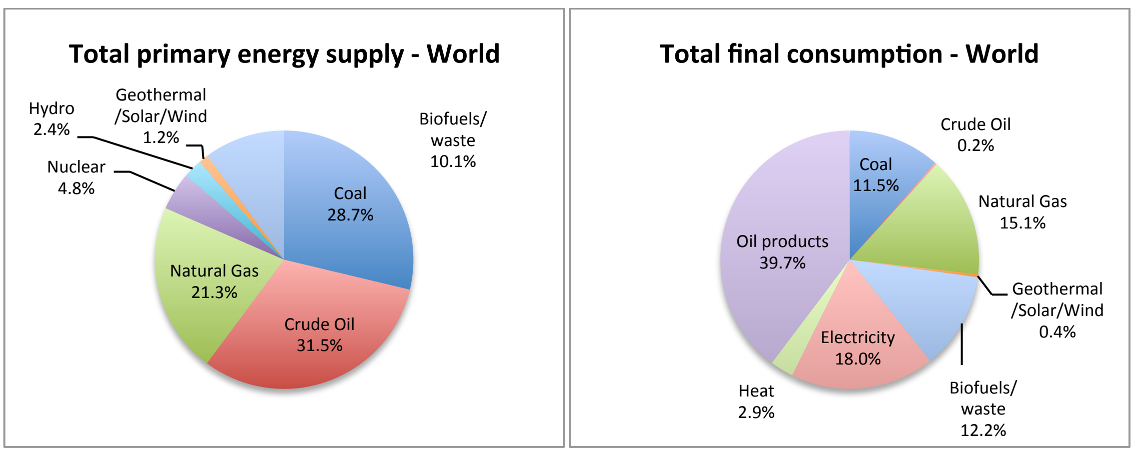


Figure 1-1: Total share of primary energy supply (left) and energy final consumption (right) in the world (data from International Energy Agency, 2015).

The particular situation of Chile is not different from the world's share. In Chile more than 60% of primary energy and more than 50% of the final consumption comes from fossil fuels (see Figure 1-2). The problem is that Chile has to import this fuel, which implicates a high-energy dependence, price volatility and supply risk.

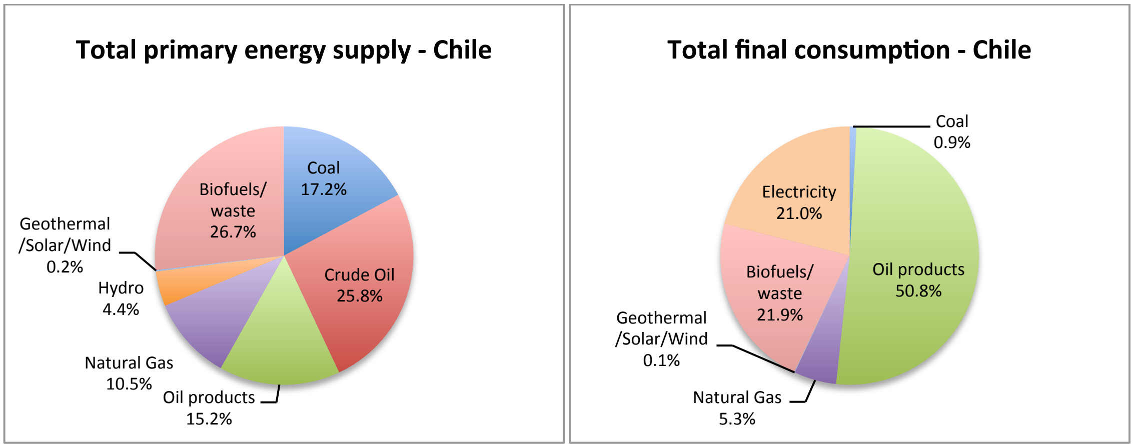
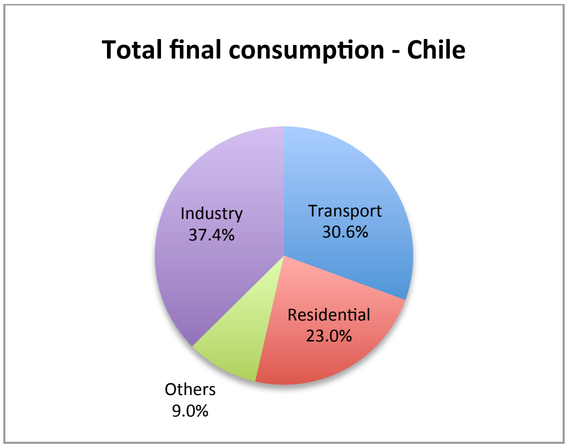


Figure 1-2: Total share of primary energy supply (left) and energy final consumption (right) in Chile (data from International Energy Agency, 2013).

Due to this urgent need for searching energetic alternatives for replacing fossil fuels, countries are opting for clean and sustainable energies that have minimum environmental impact but at the same time are feasible and can help with economic development. Chile is one of these countries and new alternatives are being proposed and developed.

The main consumers of energy in Chile are the industry and transport sectors (see Figure 1-3). In the industry area, the majority of consumption for their production is electricity and heat, which nowadays it is mainly produced by fossil fuels or by biofuels and waste. This fuel can be replaced by renewable energies such as solar, which can provide electricity and thermal energy.



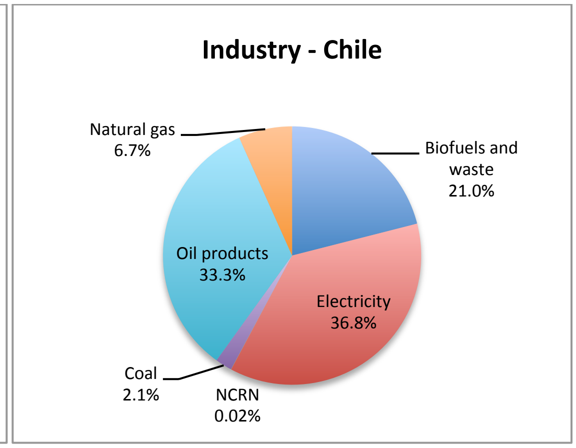


Figure 1-3: Total final consumption share per sector (left) and use of energy detail in the industry sector (right) in Chile (data from International Energy Agency, 2013).

Chile has an exceptional potential for solar energy. In the Atacama Desert, solar energy has advantages over other locations in the same country. Solar radiation in this area is one of the highest worldwide with an annual average for daily irradiation exceeding 7.5 kWh/m^2 for Global Horizontal Irradiation (GHI) and 9 kWh/m^2 for Direct Normal Irradiation (DNI) (Pino, Bueno, Escobar, & Ramos, 2015).

But not only the Atacama Desert has good radiation conditions for solar projects. In the World Solar Map (see Figure 1-4) it is possible to see that Chile has good irradiation from north to south, with better conditions than Spain or Germany that have high development of solar energy technologies. This high DNI resource makes the country optimal for solar projects.

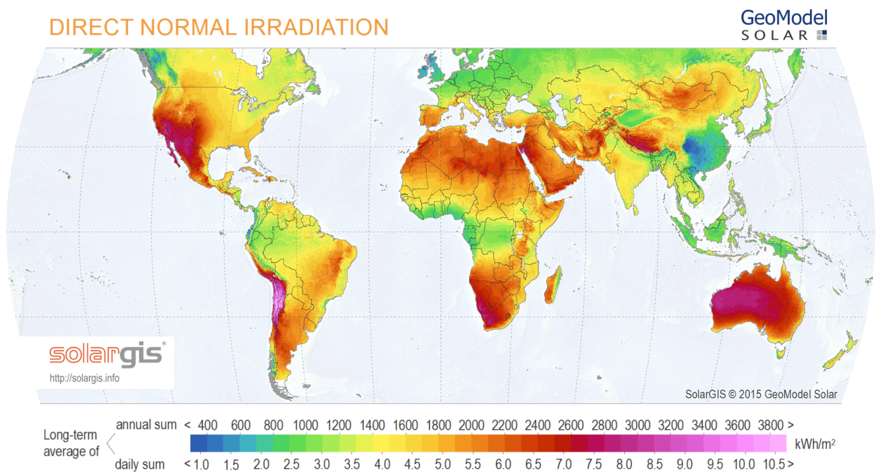


Figure 1-4: World map of Direct Normal Irradiation (GeoModel Solar, 2016)**.**

The Chilean Ministry of Energy and the *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ) made a study for presenting the potential of solar energy in Chile considering restriction of territory, capacity factor, average DNI, avergae GHI and the minimum area for projects (Santana, Falvey, Ibarra, & García, 2014). The results gave that there is a potential of 1,200 GW for fix photovoltaic (PV), 1,600 GW for tracking PV and 550 GW for Concentrating Solar Power (CSP). PV is feasible from the first region, on the north of Chile, to the Metropolitan Region (Santiago) and CSP from the first region to the Atacama Desert.

Other relevant study relating to the potential of solar energy in Chile was made by Escobar et al., 2015. Their simulation indicates the potential for residential solar thermal systems, PV systems and also for CSP technologies considering annual GHI and DNI, suitable terrain and energy demand. For residential thermal systems, most of the country can achieve solar fractions over 80%, PV systems can achieve high values of kWh/kWpv and CSP annual yields of up to 240 GWh/year for a 50 MW parabolic trough plant.

Solar projects are usually installed in arid or semi-arid areas because they have high solar resource. However, these areas have high soiling rate due to the presence of dust, lack of vegetation, wind and other factors that influence in the decrease of the mirror reflectance and thus in the output of the plant. Thus, plants have high maintenance costs because of mirror cleaning. Economic analyses indicate that it is cost-effective to maintain the average field reflectance above 90% (Heimsath, Heck, Morin, Kiewitt, & Platzer, 2010).

As was shown, northern Chile has a big potential for solar projects, however this location has limited hydric resources so there is a need of developing techniques for reducing water consumption. One proposal for this issue is to optimize the cleaning cycle so water usage can be reduce and the cleaning frequency can be defined in order to maintain a certain annual average reflectance that minimize costs of operating and maintenance of a plant.

1.2 Hypothesis and objectives

The hypothesis of this work is: Soiling in reflective surfaces of concentrating solar plants affects directly to production so soiling rate, depending on the site, must be characterized and quantified for developing an optimal cycle for cleaning the plant that minimize the frequency and the cost of cleaning.

The main objective of this work thesis is to quantify and characterize the soiling effect on reflective surfaces in Chilean climatic conditions for the optimization of cleaning cycles.

The specific objectives are:

- Study and analyze different cleaning methods for thermo solar plants.
- Review the impact of decreasing the reflectance of mirrors on the output of the plant.
- Review cleaning costs according to the total collector area of the plant.
- Define the optimal cleaning method for each range of plant size.
- Propose a method for measuring soiling rate

1.3 Solar Energy technologies

Solar energy can be used in two main applications as displayed in Figure 1-5. The first one is to convert the sunlight directly to electricity (solar photovoltaic) and the second one is to use irradiation to heat a fluid for further use (solar thermal).

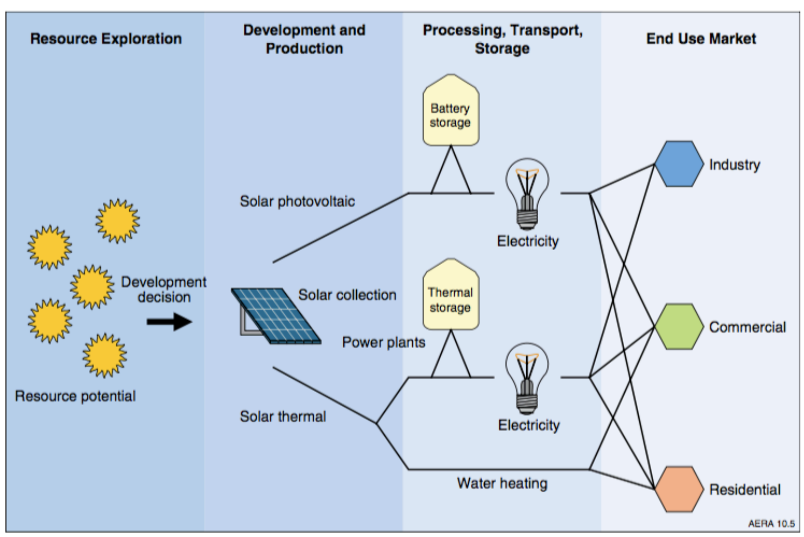


Figure 1-5: General classification of different types of solar energy (Carson, 2014).

Photovoltaic panels (PV) convert solar radiation directly into electricity by using photovoltaic cells. This can be used for a household, in buildings or even be expanded on a large scale and create power generation plants that inject electricity directly into the grid.

PV technology has the disadvantage that it is not an energy source with continuous supply, because it depends on the hours of sunlight available. The conventional form of storage, such as batteries, is expensive and is not cost-effective to store large amounts of energy. However, today there are thermal energy storage technologies that allow continuous production to meet the energy demands. This is the main reason that in this work thermal technologies will be studied.

Solar thermal technologies transform solar radiation directly to heat through a working fluid. It can be used for heating or for electricity generation. Heating is for domestic use (water heating) or process heat (food production, industrial, mining, etc.). Electricity is generated through concentrating solar power plants (CSP), which concentrate solar radiation to generate high temperatures so it can be used in a conventional power cycle.

The main uses of heating are dependent of their temperature. Low temperature is used for domestic use, hot water use or space heating. Mid temperatures are used for industrial use such as solar cooling or other low temperature process. For obtaining higher temperatures, for industrial process heat, it is possible to use concentrating technologies with reflective mirrors (see Figure 1-6).

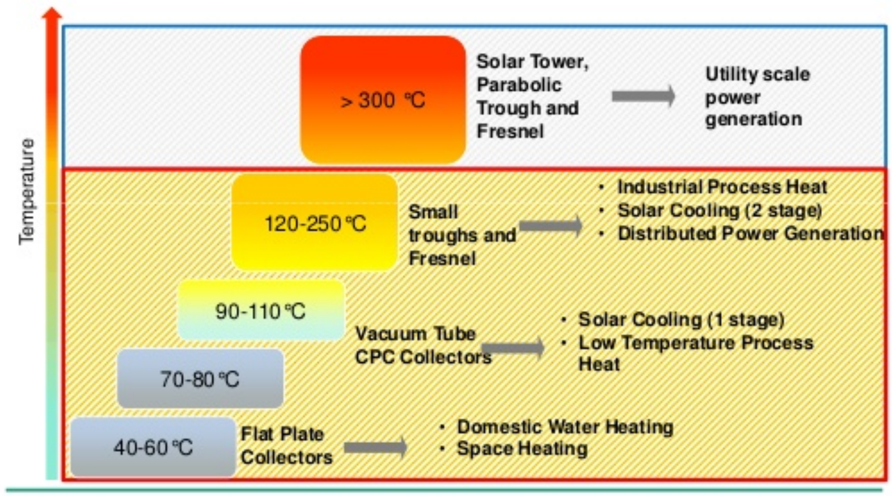


Figure 1-6: Solar Thermal Collectors for Power, Cooling and Heat (Platzer, 2015).

CSP plants use reflective mirrors, called collectors, which reflect radiation onto an abosrber tube with a heat transfer fluid inside, transforming sun energy into thermal energy. After this, the fluid goes onto a heat storage system, which allows them to operate when there is no radiation such as cloudy days or nighttime. Finally, the fluid passes through a heat exchanger to create steam and using it in a conventional power cycle (See Figure 1-7).

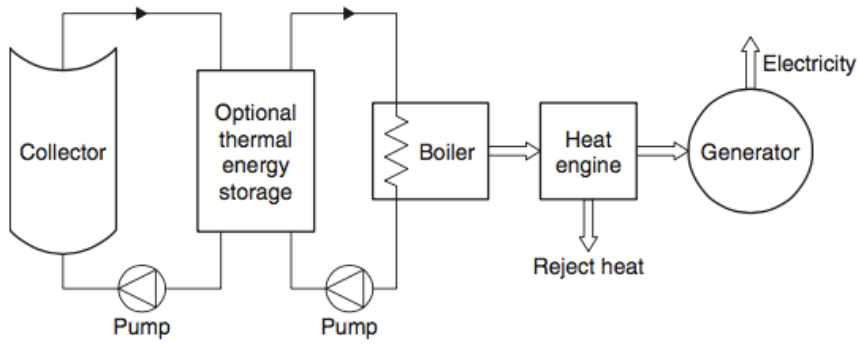


Figure 1-7: Schematic diagram of energy conversion system of a CSP plant (Kalogirou, 2014).

Mirrors used in the collector must meet three key criteria; be highly reflective over the solar spectrum, reflect a high degree of specularity and should be resistant to environmental damage such as wind, high and low temperatures, contamination, among others (Augsten, 2011; Meyen et al., 2010).

Concentrated solar plants are divided into four technologies: Parabolic Trough Collectors (PTC), Linear Fresnel Collectors, Dish Collectors, and Solar Central Tower (SCT). All four types have the same functioning principle as described before but differ on the collecting system. Technologies will be described in the following sections.

1.3.1 Solar Central Tower (SCT)

SCT uses thousand of flat reflective mirrors called heliostats for reflecting the sunlight to the central receiver, which is located on the top of a tower. The receiver transforms the reflected DNI into thermal energy, transferring the heat into a fluid. This fluid is transported to a power conversion system to produce electricity in a conventional power cycle. This technology has a molten salt storage for generating electric energy when sunlight is not available.

On the construction phase of a plant, heliostats represent around 50% of the cost; so reducing its cost is a fundamental issue for the economic feasibility of the plant. Efforts have been focus in searching cheaper material that do not compromise reflectance (Kolb et al., 2007).

Central tower plants are usually designed for large scale, being built and designed for power ranges from 10 MW to 100 MW. The first plant was constructed in California by the US Department of Energy and was a 10 MW plant called Solar One. This plant operated successfully for 4 years from 1982, but then stopped its operation because of heat transfer fluid problems (Kalogirou, 2014).

The first molten salt storage plant was Solar Two. It was built in order to improve the problems of Solar One. Solar One's heliostats were of 40 m^2 and for Solar Two they added a second ring of heliostats of 90 m^2 each.

The next tower plants constructed were PS10 and PS20 in Seville, Spain. These commercial plants are currently operating. Their heliostats were a new generation of bigger mirrors of 120 m^2. The size increase was made in order to improve economies of scale and reduce cost.

The next important step in the development of this technology was the construction of Gemasolar, which was the first plant able to supply uninterrupted power for 24 hours. This plant has a capacity of 19.9 MW and injected its power to the grid.

The material of the heliostats of Solar One and Solar Two was of laminated glass-based mirror. This mirror is a multilayer glass that has a silvered coating for turning transparent glass into a mirror. For protecting this coating, a back plate is laminated on the back.

The heliostat material of PS10, PS20 and Gemasolar are also of a glass-based mirror, but differ from the laminated of Solar Two in its single sheet of glass (monolithic), thus instead of the laminated plate in the back it has a multi-layer coating that is applied in a chemical process for protecting it from environmental effects (see Figure 1-8).

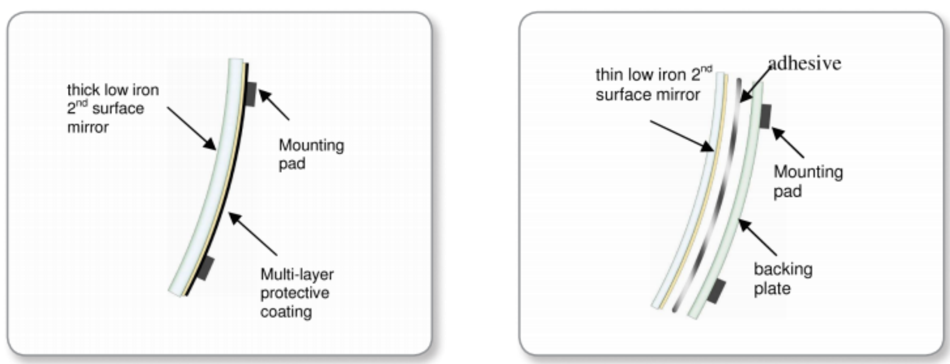


Figure 1-8: Difference between two types of glass based CSP mirrors; monolithic mirror (left) and multilayer laminated mirror (right) (from Wang, Vandal, & Thomsen, 2010).

Glass mirror is the most popular material in CSP plants because it has high optical properties (95% weighted hemispherical reflectance), high specularity and durability in a variety of climates. However, these have the disadvantage of having a high manufacturing cost and are fragile, making difficult its transportation.

1.3.2 Parabolic Trough Collector

A parabolic trough collector reflects solar radiation onto one axis. This collector has a single axis tracking mechanism for following the sun direction. The receiver tube is located in the focal line of the parabola with a working fluid inside.

Parabolic trough collector technology can be used for power generation plants or for process heat applications (high temperature). For the case of power generation, the principle is similar to central tower technology, in which the working fluid passes through a heat exchanger and is used on a conventional power cycle. For process heat, the fluid passes directly to a heat exchanger and can be used immediately. Both applications can be used with thermal storage.

The collector is a metal structure that serves a support for the mirrors. The receiver tube, the supports and the tracking system are installed in the structure. The material of mirrors is similar than the central tower technology but more innovations have been done.

The first big scale power plant was constructed in southern California. The project named Solar Electric Generating Systems (SEGS) is an installation of nine plants that in total have an installed capacity of 354 MWe (Kalogirou, 2014). The reflective surface of this plant is of monolithic mirror glass.

The mirror glass used in this plant is a low-iron 4mm thick glass, which is heated in special ovens for obtaining the parabolic shape of the collector. Then, mirrors are coated by a silvered film on the back (Price et al., 2002). This material is highly reflective and with high durability, but has high cost and they are easily breakable.

Innovations in mirror materials have been made in order to find lower costs and lighter collectors. Anodized aluminum and polymer films are the options for replacing the mirrors, however durability and high reflectivity need to be similar than glass mirror.

Anodized aluminum material is a layer of aluminum that has a coating of a PVD layer that guarantees a high reflectance (See Figure 1-9). PVD stands for physical vapor deposition, which is applied for achieving a maximum total light reflection. In addition, other layers are added for protection against outdoor conditions. Its solar direct reflectance is between 86.8 and 88.3% but its is considered to have low specularity, so its specular reflectance can be around 75% (Augsten, 2011).

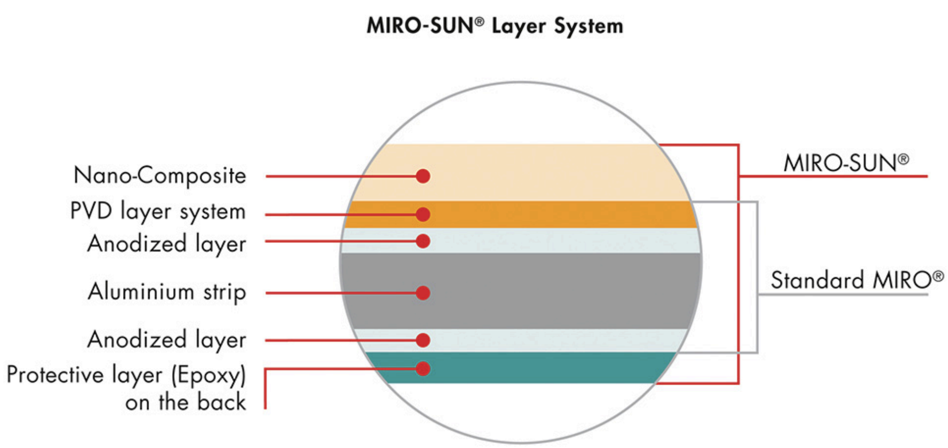


Figure 1-9: Anodized aluminum film layers description. MIRO-SUN layer is produced by Alanod (Alanod Solar, 2016).

The anodized aluminum is an inexpensive material, lightweight and with mechanical benefits, but its durability in outdoor conditions is less than glass mirrors. Studies by NREL (National Renewable Energy Laboratory) and DLR *(Deutsches Zentrum für Luft-*

und Raumfahrt) were performed in eight sites, 6 in the US and 2 in Europe. Three samples of each material were tested for 6 month and then measured. The study, confirmed that in outdoor applications specular reflectance decreases severely so these mirrors are not ideal for high concentration (Fend, Jorgensen, & Küster, 2000).

Polymeric films are a silvered metallized weatherable acrylic film. This material is inexpensive, lightweight and its optical properties are quite similar to those of glass mirror. These mirrors have a 94.5% of solar weighted hemispheric reflectance with high specularity (Padiyath, 2013).

They also have the advantage of being able to obtain a greater focal distance for concentration technologies by low weight and flexibility. For example, parabolic trough mirrors up to 7.3 meters aperture where build with these sheets, improving the concentration factor and the accuracy of focus (technology designed and built by Gossamer Space Frames and 3M).

1.3.3 Linear Fresnel Collectors

The linear Fresnel is similar to the parabolic trough, both reflect radiation into one lineal axis and can produce thermal energy for process heat or power generation. The difference is that the collector is an array of flat mirrors and that he receptor is fixed so the is less probability that the junctures fail. This technology achieves lower temperatures because the focus is weaker, but its cost is lower because there is no need for curvature on the mirrors.

The material of the collector is similar to central tower heliostats. Both can use glass based mirrors but Fresnel technology has the advantage that doesn't need to reflect radiation to high distances so it can use technologies with less specular reflectance such as new technologies (polymer films and aluminum mirrors).

1.3.4 Dish Collectors

Dish collector technology is a dish parabolic mirror that reflects radiation on the focus where the receiver is mounted. The receiver transforms solar energy into thermal energy, which can be used for direct heat use, process heat or in power generation.

The collector is an array of flat mirrors that together form a parabolic shape. The most common material is thin and thick glass mirror, but new materials such as low cost aluminum and polymer films are suitable.

Dish collectors have not wide development compared to the other three solar concentrating configurations, however it has the potential of being a low cost and efficient technology. The advantage of this system is it has the higher of solar to electric efficiencies, modular and suitable for small scale area with each unit typically generating output of 3 to 25 kW (Affandi, Ghani, Ghan, & Pheng, 2015).

1.4 Solar development in Chile

At present, solar projects have had a high growth in Chile. Table 1-1 shows the electric status of renewable energy projects in Chile (Comité CORFO, 2016). For concentrating solar power there is still no plant in operation but one project is being constructed and some others are being developed.

Table 1-1: Installed capacity of renewable energy projects in different stage of the environmental assessment measured in MW (from CORFO, April 2016).

Technology	Operation	Construction	Approved	Under evaluation
Biomass	417	0	112	47
Biogas	53	0	8	0
Eolic	910	428	5,966	1,905
Geothermal	0	48	120	0
Mini Hydro	433	25	455	82
Solar PV	1,102	2,082	11,363	5,296
Solar CSP	0	110	980	925
TOTAL	2,916	2,692	19,004	8,255

The first CSP project in construction in Chile is a central tower technology solar plant developed by Abengoa. This project, *Atacama Solar 1*, has 110 MW of CSP power and 17.5 hours of thermal storage. Two other projects are under development. The first one is form Solar Reserve and is a 260 MW project called *Copiapó Solar*. Ibereólica is developing the second project and is a 360 MW called *Pedro de Valdivia*.

Thermal energy generation has also being developed. The first project was a parabolic trough project of 12 MW_{th} developed by Abengoa for *Centinela* mining from *Antofagasta Minerals*. Another mining project was a 25.5 MW_{th} flat plate collector plant developed by Sunmark in the *Gabriela Mistral* mining from CODELCO. Both solar plant produces between 80-85% of heat demand for the copper extraction process.

1.5 State of Art

1.5.1 Reflectivity

In concentrating solar plants, mirrors are the basis of their performance. These are the surfaces that reflect the solar radiation to the receiver tracking the sun in one or two axes. They have reflective characteristics depending on their material, but generally they have a high quality standard to ensure high efficiency that maximizes the reflectance of sunlight across the spectrum.

In general, the term *reflectivity* is used as an intensive property of a reflective material. The term *reflectance* depends on the quantity of matter and the given conditions (Fernández García, 2012). That is why in this work the term "reflectance" is used to refer to the radiation reflected by a body.

Sunlight falling on a surface is reflected, absorbed and transmitted in different proportions. These ratios are given by the material properties shown below (Meyen, Montecchi, Kennedy, & Zhu, 2013):

1. Reflectance (ρ): Fraction of incident energy reflected by the surface.

$$\rho = \frac{\phi_r}{\phi_i} \tag{1-1}$$

   Where ϕ_r is the energy reflected by the surface and ϕ_i is the incident energy.

2. Absortance (α): Fraction of incident energy on a surface absorbed by the body.

3. Transmittance (τ): Fraction of incident energy transmitted through the surface.

These three properties are subject to the law of conservation of energy, which states that they are related according to Equation (1-2). For application in solar thermal plants the parameter of interest is the reflectance.

$$\alpha + \rho + \tau = 1 \tag{1-2}$$

The hemispherical reflectance (ρ_h) is described as the total amount of radiation that is reflected back into the hemisphere on the reflective surface, which is divided between the diffuse and specular radiation. This depends on the wavelength (λ) and the angle of incidence (θ) of the incident light beam.

Specular reflectance (ρ_s) is the light reflected in an opposite direction to the incident light angle. However, the surfaces are generally slightly irregular so the beam of specular light reflected is defined as a profile within an opening angle or acceptance (φ) as shown in Figure 1-10. Specular reflectance depends of the wavelength (λ) of incident light angle (θ) and acceptance half angle (φ). Alternatively, it can be defined as the hemispherical reflectance minus the diffuse light outside the acceptance angle φ.

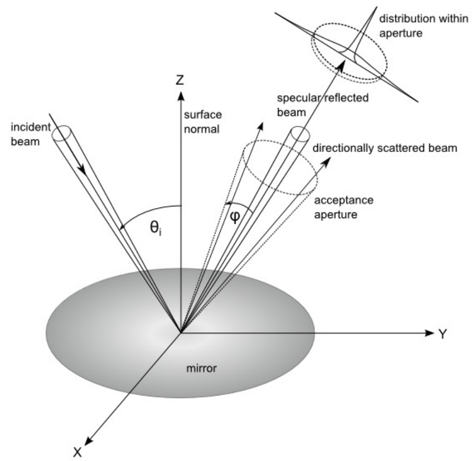


Figure 1-10: Specular reflectance for an angle of incidence θ and an angle of acceptance φ (from Meyen et al., 2013).

In a perfectly smooth mirror, specular reflectance is equal to the direct reflectance as the whole reflected light is collected within the specular beam and no diffusion occurs. However, surfaces are slightly irregular and this causes specular reflected beam to broaden in one σ_{spec} angle. All the reflected light within a selected opening around 25 mrad, located around ρ_s is defined as the direct reflectance (ρ_{direct}) (Meyen et al., 2013).

For use in solar thermal technologies, the values described above must be weighted for the entire range of the solar spectrum. The weighting is done according to ASTM G173 standard terrestrial solar spectrum at air mass AM1.5. Thus we obtain the hemispherical solar reflectance weighted (ρ_{swh}) and solar weighted specular reflectance (ρ_{sws}), considering the angle of acceptance. The latter is the most important because is the one to be considered for solar simulation and which characterizes the quality and performance of solar mirrors.

Devices measuring reflectivity properties of the materials are divided into two categories: spectrophotometers and reflectometers. The first measures the spectral reflectance and reflectometers generally measure monochromatic specular reflectance (for a defined wavelength).

According to Meyen et al. (2013) an ideal reflectometer should measure reflectance at wavelengths between 280 nm and 2500 nm at intervals of 5 nm and has to be able to define controllable acceptance angles. However, there are currently no sufficiently accurate instruments that can deliver accurate data so approximations must be used and values in spectral ranges.

The most widely used market instrument, is the Device and Services D&S15R. This portable device is capable of measuring at two wavelengths (550 or 660 nm) and has four adjustable acceptance angles. However, this device has the disadvantage that measures one point at a time, but it can be used on the field.

Other portable reflectometer instrument is the Condor SR-6.1 developed by Abengoa Solar that has a focus on usability and applications in operations and maintenance (Crawford, Stewart, & Pérez-ullivarri, 2012). Another reflectometer also used for measuring is the SOC 410 Solar developed by Surface Optics that can measure hemispherical and diffuse reflectance but not specular as the other two can.

New measuring instruments are being researched and developed, looking for more accurate measurements for specific applications, such as soiling characterization. Among these innovations is the instrument called TraCS (Tracking Cleanliness System) developed by German researchers (Wolfertstetter et al., 2012).

The Cleanliness Tracking Sensor (TraCS) is an instrument for measuring loss in solar reflectance mirrors. This instrument enables more accurate measurement easier and more cost effective to measure levels of contamination of the mirrors.

The advantage of this instrument on the classic market reflectometers is that it allows continuous measurements in real time, allowing the optimization of solar plants cleaning cycles. In addition, measurements are made with natural light (DNI) and not with LED light as reflectometers.

The TraCS uses conventional stations that include a solar tracker, in which a pyrheliometer is needed for measuring direct normal irradiance (DNI). The TraCS is coupled to the same station as a second pyrheliometer mounted in the opposite direction, so that points to a mirror and not directly to the sun.

TraCS measures the direct radiation delivered by the mirror, which is a fraction of the DNI reaching the mirror. To calculate which is the loss of reflectance mirror reflected radiation is divided at that moment by the DNI at that moment.

1.5.2 Soiling rate

Solar thermal concentrating plants usually are installed in places with characteristics of arid climate, where there is little rainfall and presence of high dust and dirt. These factors make mirror soiling more regular and its efficiency decreases.

There are multiple studies that analyses the effect of soiling in mirrors according to the climate. One of these studies is from Herrmann et al. (2014), they used geographic information systems (GIS) for generating information layers in order to create maps that represent the potential soiling, which in this case the area covered is North Africa and the Middle East.

For calculating the potential soiling they considered characteristics of the emission of dust from the ground into the air (soil properties, surface conditions and the wind speed). Then, they analyzed how dust is transported which was mainly because of speed and direction of the wind. At last, they analyzed how dust was deposited on the ground and collector, which was related with environmental a technical parameters. With this result they created a risk map in which indicates the zones with more soiling potential.

The soiling rate of mirrors depends on the climatic characteristics of the site, grounds and solid characteristics and on the reflective surface being used. In order to calculate this value exposure tests must be performed, indicating the value of the soiling rate for different months and seasons.

There are publications where values for soiling rate in different parts of the world are presented. First we have the study by Heimsath et al. (2010) which provides values for three different locations (Freiburg in Germany, Sicily in Italy and the Negev desert in Israel) for two different types of materials (anodized aluminum and monolithic glass mirrors). The methodology used is that they make direct measurements of reflectance with an instrument designed by them, which is a spectrometer that measures at wavelengths between 430 nm and 730 connected to an optical head. The mirrors were placed in different locations for a specified period (100 days) without being cleaned and then taken to the laboratory for measurement.

The average results of this study are shown in Table 1-2. Also, in the same publication mentions an example of California where soiling rates values used for summer were 0.47% per day in winter and 0.16% per day.

Table 1-2: Average soiling rate values (%/day) for different locations for two types of mirrors. Values of Florida and Arizona are measurements of the IEA (International Energy Agency).

	Freiburg	Sicilia	Negev Desert	Florida (USA)	Arizona (USA)
Anodized aluminum	0.022-0.98	0.005-0.068	0.139-0.148	0.023-0.046	---
Glass Mirror	0.013-1.32	0.009-0.058	0.134-0.154	0.007-0.066	0.004-0.038

Another relevant study on this subject was conducted by Griffith, Vhengani, & Maliage (2013). They measured the soiling rate in a site near Kathu in the Northern Cape, South Africa. They measured reflectance of monolithic glass mirrors every two weeks. The instrument used was one designed by them consisting of imaging and analysis of pixels.

The results of this study shows that daily losses ranging from 0.32 to 1.13%, and on average is 0.5%, which means that a plant in 10 days can reach 97.5% of its reflectance compared to its initial state.

For Chile, there are still no measurements for soiling rate. However it is known that in the north the climate is arid and with atmospheric dust, so the effect of soiling can be high. It is important to calculate this value and also model what would be the effect of this on the output of the solar plant.

1.5.3 Cleaning methods

Due to the high soiling presented in the reflective surfaces, cleaning is needed to keep the reflectance of the mirrors high and to not affect the energy production of the solar plant. A 1% of decrease in reflectance due to soiling could mean a 1.2% decrease of performance (Cohen, Kearney, & Kolb, 1999). There are different cleaning methods, which differ according to the resources they use and efficiency of cleaning.

Traditional cleaning methods are demineralized water (brush or pressure), pressurized air and the rotating brush (without water). These traditional methods are combined together to create technologies that optimize the cleaning of the plant, such as trucks or cleaning robots.

Methods with demineralized water consist in a washer with a water tank in which accessories can be connected for the cleaning function. Two principal accessories are used, a hand spray nozzle for cleaning with pressurized water and a water-fed bristle brush for scrubbing the surface.

The pressurized air method consists of a compressor that raises the pressure of atmospheric air and ejects it at high speed to clean surfaces. This method spreads the dust around so it is only suitable for small installations.

The rotating-brush is a waterless method. This achieves clean surfaces powder surface but is not able to remove small particles or those high adhesiveness. In addition, the machines are powerful electrically duty brush and its maintenance is difficult (mobile parts).

Researchers from the *Plataforma Solar de Almeria* compared different cleaning methods. According to their study, the method which better maintain the reflectivity of the mirrors in arid and desert conditions (summer) is demineralized water with brush without using any detergent (Fernández-García et al., 2013). However, this method is water-intensive, ranging from 0.3 to 0.7 l/m^2, whereas to recover 98.3% of the reflectance, 3 cleaning cycles within a frequency of 2 weeks must be applied.

Traditional methods have proven to be effective in terms of cleanliness however they have intensive resources usage that rise the cost of maintenance in solar plants. The methods used with demineralized water use high volume of water resources, which is costly in arid areas, and air pressure method requires a high-energy consumption. This is the reason why there have been several innovations in this area and have been created waterless cleaning technology, without manual labor or moving parts (He, Zhou, & Li, 2011).

One innovative technology without water is the self-cleaning layer with high hydrophilicity that consist of a nano transparent TiO_2 film that is installed in the panels (heliostats or photovoltaic) and generates two separate processes that together produce the cleaning of the panel. First, a photocatalytic process in which the TiO_2 reacts with ultraviolet light separating dust from the panel. The second stage is the hydrophilicity, in which rain draggs dust outside panel. This process is efficient but has the disadvantage that rain water is required, which in arid locations is not applicable.

Another technology is the highly hydrophobic layers that clean the panel with falling rain and drag dust particles. This layer increases the contact angle of water with the surface causing water to be deposited as drops. Then these drops slide down the panel by dragging all kinds of dust or dirt.

On the other hand, there are methods based on electrostatic forces in order to remove dust from the mirrors. This method called Electrodynamic Screen (EDS) consists of rows of parallel electrodes embedded in a transparent dielectric film that when connected to an AC three-phase particles are charged and thus removed by electrostatic forces and moved by the electromagnetic field generated (Mazumder et al., 2013).

Waterless new technologies are innovations that are still been developed and their implementation has a high investment cost. Currently, concentrated solar plants use different cleaning methods ranging from traditional simple methods to car driven robots that mix different methods for optimum reflectance values.

Below different cleaning methods and its main features are described.

i. Trucks cleaning: cleaning trucks are most commonly used in solar concentration plants of large power. This is a truck with a water tank around 9000 liters which will fit various cleaning utensils. These trucks combine brush cleaning, dilution and high pressure, using an average of 0.7 l/m^2 of water. This technology is applicable for heliostats (solar tower) and for parabolic trough mirrors.

ii. Self-propelled trucks: The US company eSolar developed a semi-automatic cleaning system for heliostats (Schell, 2011). This self-propelled truck has nozzles that spray high-pressure demineralized water. The vehicle can operate autonomously with high water usage as well as cleaning time. The cleaning process takes 10 min to clean 239 m^2 of reflective surface and uses only one operator to run several vehicles (for filling the water tank and for repositioning the machine). Is made for flat heliostats, but it is possible to find on the market similar technologies that serve for parabolic trough (Vicente et al., 2012).

iii. Automatic robots: These cleaning robots, first developed by the company Sener are robots which act autonomously to clean the mirror through brushing with demineralized water. They have the advantage of being small, light and reduce manual labor. They are specifically designed for flat collectors, so serve to heliostats or for photovoltaic modules.

iv. Manual cleaning: This method uses a cleaning utensil operated by one person. This can be done through mobile platforms and clean with pressurized water, brush or other methods.

2 ARTICLE

2.1 Introduction

Global warming is an international issue and this is because of the increase in greenhouse gases (GHG) in the atmosphere. One of the main reasons for GHG increase is the high usage of fossil fuels, which are the main base for energy production in the world. More than 60% of primary energy and final consumption depends on fossil fuels (International Energy Agency, 2015).

In this context, renewable energy has gain popularity and technologies such as concentrating solar plants have been developed in several countries around the world. Solar thermal plants usually are located in arid or semi-arid areas, where solar radiation resource is high. Therefore, these locations have high rates of contamination by the presence of dust, wind and other factors, which reduces the reflectivity of the mirrors and the output of the solar plant. In consequence, these plants lead to major maintenance costs for cleaning the mirrors.

Soiling is a crucial factor in the maintenance of a thermal plant. Mirrors can decrease its reflectance on values than can achieve 1.5% per day (Griffith et al., 2013; Heimsath et al., 2010). Calculating the soiling rate on the location of a solar plant is necessary for knowing the impact on the output, considering that a decrease in 1% of mirror reflectance can affect in 1.2% of the plant performance (Cohen et al., 1999). This means than in a month, due to soiling, the thermo solar plant can produce 30% less of thermal energy than with clean mirrors.

To reduce the effect of soiling, cleaning is needed. However, cleaning means use of water, manual labor and other resources that increases the maintenance of the plant. An optimization must be performed to find the balance between maintaining high reflectivity for system performance and cleaning frequency.

In this paper a soiling exposure test is made for measuring the soiling rate on a particular site in Central Chile. Samples of polymeric films and glass mirror are exposed for a period of a month and weekly measurements are made for calculating an average value for the soiling rate.

The second part of the paper is an optimization model for obtaining the recommended cleaning cycle of the reflective mirrors of a solar plant. The soiling rate of the site is the main input of the model. The results of the exposure test are use for the simulation and verification of the model.

2.2 State of art – Reflective mirrors

In concentrating solar plants, reflective mirrors are the basis of their performance. These are the surfaces that reflect the solar radiation to the receiver. They have reflective characteristics depending on their material, but generally they have a high quality standard to ensure high efficiency that maximizes the reflectance of sunlight across the spectrum.

The hemispherical reflectance (ρ_h) is described as the total amount of radiation that is reflected back into the hemisphere on the reflective surface, which is divided between the diffuse and specular radiation. This depends on the wavelength (λ) and the angle of incidence (θ) of the incident light beam (Meyen et al., 2013).

Specular reflectance (ρ_s) is the light reflected in an opposite direction to the incident light angle. The beam of specular light reflected is defined as a profile within an opening angle or acceptance (φ) as shown in Figure 2-1. Specular reflectance depends of the wavelength (λ) of incident light angle (θ) and acceptance half angle (φ). Alternatively, it can be defined as the hemispherical reflectance minus the diffuse light outside the acceptance angle φ.

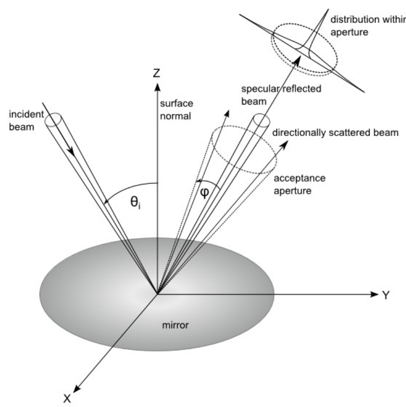


Figure 2-1: Specular reflectance for an angle of incidence θ and φ an angle of acceptance (Meyen et al., 2013).

In a perfectly smooth mirror, specular reflectance is equal to the direct reflectance as the whole reflected light is collected within the specular beam and no diffusion occurs. However, surfaces are slightly irregular and this causes specular reflected beam to broaden in one σ_{spec} angle. All the reflected light within a selected opening around 25 mrad, located around ρ_s is defined as the direct reflectance (ρ_{direct}) (Meyen et al., 2013)

Glass mirror is the most popular material in concentrating solar plants because it has high optical properties (95% weighted hemispherical reflectance), high specularity and durability in a variety of climates. However, these have the disadvantage of having a high manufacturing cost and are fragile, making difficult their transportation.

There are two types of Glass mirror configuraation. First, the laminated glass-based mirror is a multilayer glass that has a silvered coating for turning transparent glass into a mirror. For protecting this coating, a back plate is laminated on the back. Other type of glass mirror is the monolothic glass, that in contrary with the laminated plate, in the back it has a multi-layer coating that is applied in a chemical process for protecting it from environmental effects.

Innovations in mirror materials have been made in order to find lower costs and lightweight collectors. Anodized aluminum and polymer films are alternatives for replacing the mirrors, however durability and high reflectivity need to be similar than glass mirror techonologies.

Anodized aluminum films are layers of aluminum that have a coating of a PVD layer that guarantees a high reflectance. PVD stands for physical vapor deposition, which is applied for achieving a maximum total light reflection. In addition other layers are added for protection against outdoor conditions. Its solar direct reflectance is between 86.8 and 88.3% but it have low specularity, so its specular reflectance is around 75% (Augsten, 2011).

The anodized aluminum is an inexpensive material, lightweight and with mechanical benefits, but its durability in outdoor conditions is lower than glass mirrors. Studies by National Renewable Energy Laboratory (NREL) and Deutsches Zentrum für Luft- und Raumfahrt (DLR) were performed in eight sites for six months. The study, confirmed that in outdoor applications specular reflectance decreases severely so these mirrors are not ideal for high concentration (Fend et al., 2000).

Polymeric film IS a reflective metallized film over a silvered glass mirror. This material is inexpensive, lightweight and its optical properties are quite similar to those of glass mirror. It has a solar weighted hemispheric reflectance of 94.5% with high specularity.

Due to its low weight and flexibility, polymeric films have the advantage of being able to obtain a greater focal distance for concentration technologies. For example, parabolic trough mirrors up to 7.3 meters aperture with these sheets have been built, improving the concentration factor and the accuracy of focus (technology designed and built by Gossamer Space Frames and 3M).

2.3 Soiling exposure test

2.3.1 Experimental setup

Exposure tests were installed in the countryside of San Felipe, located in the Aconcagua Province in central Chile's Valparaíso Region. The setup was installed next a to a existing parabolic trought thermal collector that supplies heat to an indsutrial process. This collector is near crop fields and near to a dust road, so it has multiple soiling inputs that need to be measured.

A stand-alone structure was designed for mounting 12 aluminum sheets of A4 size (210x297 mm). The structure has three rails with a variable angle between 0º and 90º with respect of the horizontal plane. Each rail supports four samples. The whole structure can rotate in 360º for different orientations.

The structure was installed on north orientation and each rail was fixed on 45º of inclination. On the aluminum sheets, mirror samples of 150x150 mm were installed (see Figure 2-2). Four samples of each material were studied; glass mirror, polymeric film and anodized aluminum. The last two where mounted on a glass surface in order to remain flat.

Figure 2-2: Stand-alone structure installed in San Felipe. Left: Structure with the aluminum sheets with its screws for installing the mirror samples. Right: Mirror samples installed on the aluminum sheets.

For the exposure test the Tracking Cleanliness Sensor (TraCS) is used. This instrument, developed by the German Aerospace Center (DLR) measures the losses of reflectance in solar mirrors in real time (Wolfertstetter et al., 2012). The working principle of the TraCS is the installation of two pyrheliometers, mounted on a sun tracker, one next to each other but in different directions. The first one measures the direct normal irradiance (DNI) and the second, as an accessory to the common established suntracker, is mounted such that it looks backwards into a mirror that reflects DNI (see Figure 2-3). A geared motor rotates the mirror in its plane to get average soiling values over the mirror surface, which makes TraCS even more accurate than standard reflectometers that measure on a very small surface (CSP Services, 2016).

Figure 2-3: Left: TraCS mounted to a Sun Tracker on a sun tracker in San Felipe, the mirror mounted to the plate is the reference glass mirror. Right: TraCS setup with the pyrheliometer facing the mirror (CSP Services, 2016).

The TraCS came with a reference mirror that is installed on the instrument for constant measuring data. This data collected during the month of exposure is also analized and presented in this work.

The instrument gives continuous data for calculating the "Cleanliness" of the mirrors, which is defined as the ratio between the reflectance of the mirror (ρ_d) with its clean state (ρ_0). Cleanliness indicates the relative decline of reflectance, which is useful for comparing different rates between materials (Merrouni, Wolfertstetter, Mezrhab, Wilbert, & Pitz-Paal, 2015). See Equation (2-1).

$$\text{Cleanliness} = \frac{\rho_d}{\rho_0} \tag{2-1}$$

The first step to measure the cleanliness with the TraCS is to calculate de "clean state cleanliness" ($\mathrm{C_{clean}}$); which serves as a calibration factor for the next measurements. To measure $\mathrm{C_{clean}}$, N values should be measure and then averaged (see Equation (2-2)).

$$\frac{1}{N}\sum_{n=1}^{N}\frac{DNI_{reflected,clean}(t_n)}{DNI_{sun}(t_n)} = C_{clean} = const \tag{2-2}$$

For calculating the cleanliness of the soiled mirrors it is necessary to divide the reflected DNI registered by the soiled mirror with the DNI measured from the sun (information measured with both pyrheliometers) and then divide by the calibration factor (see Equation (2-3)). Cleanliness varies continuously during periods of time (t).

$$\text{Cleanliness}(t) = \frac{DNI_{reflected,soiled}(t)}{C_{clean} \cdot DNI_{sun}(t)} \tag{2-3}$$

2.3.2 Measurements cycle

The exposure test experiment was made in a period of one moth. Every measurement was taken once a week. The experiment started the 1st of March and ended on the 29th of March. The measurements were made every week as described in Table 2-1.

Table 2-1: Measurements cycle detail for every week.

	Initial (01/03)	**Week 1 (08/03)**	**Week 2 (15/03)**	**Week 3 (22/03)**	**Week 4 (29/03**
Measurements	4 samples of each material	Sample 1 of each material (soiled)	Sample 1 and 2 of each material (soiled)	Sample 1, 2 and 3 of each material (soiled)	All samples of each material
	Define "Clean State"	Clean sample 1 of each material and measure	Clean sample 2 of each material and measure	Clean sample 3 of each material and measure	

2.3.3 Results and discussion

The first week, 12 samples were installed. For the first measurement (8 of march) several events where noticed. The first was the humidity on the surface of the mirrors during the morning. Dew affected on mirrors and left drops of water on the surface.

In the morning of the 6^{th}, 7^{th} and 8^{th} of March the relative humidity was close to 100%. This means that water drops where formed in the samples surface (see Figure 2-4 and Figure 2-5).

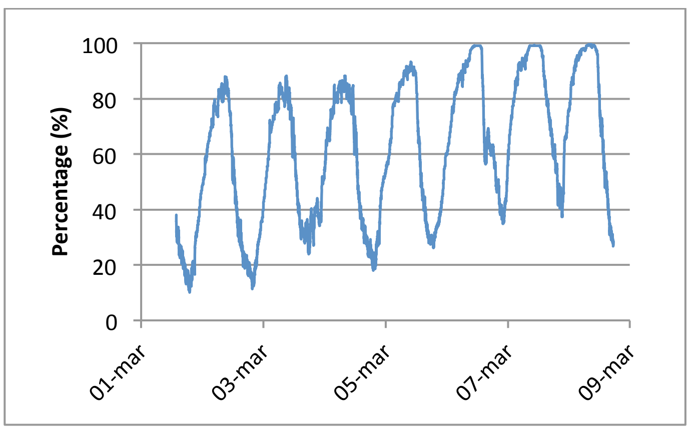


Figure 2-4: Relative humidity (%) for the first week of measurements.

Humidity was more evident in polymeric and anodized aluminum films than glass mirrors samples. The first two had big drops of water and the glass mirror only had some little drops on the corners. On the other hand, the parabolic collector didn’t have drops, just had a trace that indicated some humidity but not as much as the samples.

Figure 2-5: Pictures of samples and the collector on the 8th of March at 9.30 hrs. From left to right: anodized aluminum films, polymeric films, glass mirror and the actual parabolic trough collector.

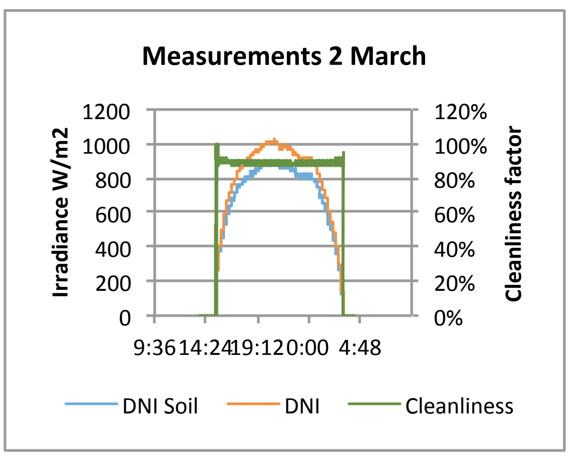
Water drop accumulation depends on different factors such as the contact angle (CA) and the roll off angle, among others. The CA is a measure of wettability of a solid by a liquid and is defined as the angle between the liquid and the surface; it's a combination between the surface tension and external forces (usually gravity). The roll-off angle is the angle of inclination of a surface at which a drop rolls off. It is an empirical variable that is highly dependent on the particular measuring conditions, such as drop size and tilt speed.

At a same tilt angle (angle between the horizontal and the mirror sample), if a surface has higher contact angle, a drop will roll off more easily. So from the expose samples, it can be notices that roll off angle is lower than 45º for mirror glass but higher for polymeric and anodized aluminum films. At the same time the drops were very circular (high superficial tension) so their contact angle was high, indicating that a slightly higher tilt angle the drops could roll off quickly. Additional testing is needed.

In the case of the solar collector, drops did not accumulate on the surface. This can be explained because during nights and morning (before the plant starts its operation) the collector is in stow position, so the tilt angle makes de drop roll off. Also, the angle of the collector protects itself from dew and humidity.

Other event noticed on the month of exposure was the cloudy days. During these days (see 3rd of March on Figure 2-6) the cleanliness measurements were not constant and values were out of normal range, so those data could not be processed and considered.

On sunny days (see 2nd of March on Figure 2-6) the cleanliness factor maintain constant during the day except on sunrise and sunset, where it can achieve values 10% higher than average for a period of approximately 5 minutes. Those values where not included in the analysis because the cause of that deviation is not defined yet. Values started being considered when the difference between one data and the next one was lower than 5%.



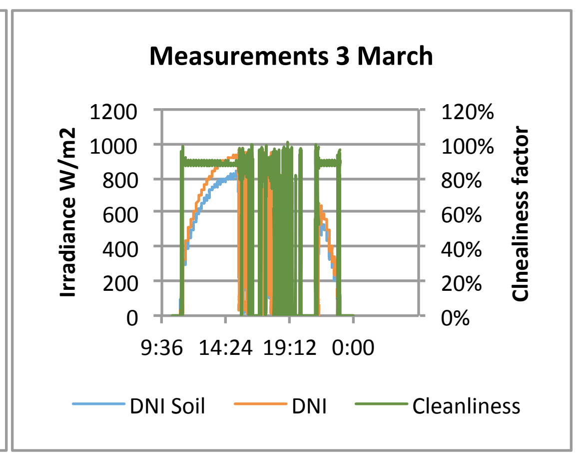


Figure 2-6: Measurements for two days from the reference glass mirror mounted on the TraCS. The 2nd of March was a sunny day but the 3rd of March presence of clouds can be observed.

On the first week, cleanliness measurements for anodized aluminum samples were higher than its initial. This was explained because the samples were not completely flat and couldn't be totally stick on the mirror base, so radiation was being concentrated into the TraCS's pyrheliometer. Data from this sample was ignored and the next 3 weeks only polymeric films and mirror glass samples where considered.

Figure 2-7 shows the results of the measurement cycle for polymeric films and glass mirrors. Whenever the samples were cleaned, the cleanliness was restore even if they didn't necessary achieve their initial reflectance (because reflectance measured by the TraCS is relative).

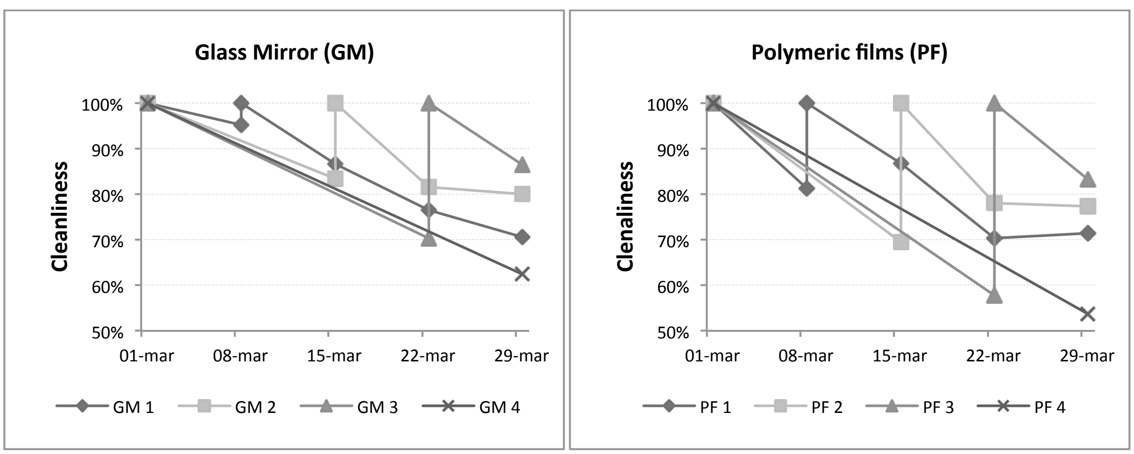


Figure 2-7: Cleanliness measurements for each sample of glass mirrors and polymeric films tests. Every point is an average of data measured every 10 s for 10 minutes (time in which the motor completes a rotation of the mirror). Measurements presented are according to the schedule described in Table 2-1.

Results of the cleanliness reduction for each material are presented in Figure 2-8. Polymeric films soiled faster than the glass mirror samples. At the end of the fourth week the polymeric film samples had around 50% of their initial reflectance and the glass mirror samples around 60%. The soling rate of polymeric films was 1.69% per day and of glas mirror was 1.36% (considering first day and last day cleanliness). This indicates that for this particular climate conditions the polymeric films have more adhesion to dust, so their reflectance decrease faster.

Otherwise, if we consider that every week the weather conditions were different (wind, humidity, temperature) the average for every week measurement for 3M was 2.14% per day and for Rioglass was 1.16%. Every week had a different soiling rate; this value is highly sensitive to variations on weather. For example, between the 22nd and 28th of March, days where cloudy, with 100% of relative humidity (not raining) and soiling was lower than in other weeks. This could have been because the excess of dew on the surface helped with the cleaning of the mirrors.

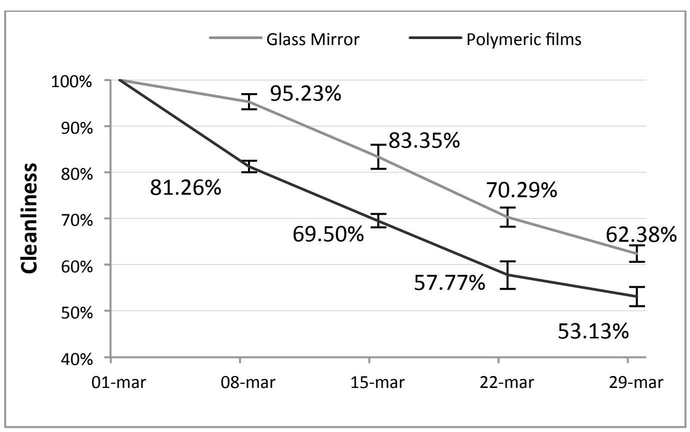


Figure 2-8: Cleanliness measurements for glass mirror and polymeric films materials. Every point is an average of data measured every 10 s for 10 minutes.

On the other hand, the measurement of soiling rate of the reference mirror installed on the TraCS gave different results (see Figure 2-9). This sample moved along with the pyrheliometer, so it was constantly tracking the sun. Soiling rate was lower than the samples installed on the stand-alone structure. On average the soiling rate was 1.19% per day.

The lower soiling rate might be explained by the fact that the TraCS was constantly moving, so its tilt angle changed with time. This made dust particles that where not totally stuck to surface roll off with mayor angles. Also, during nightime the suntracker goes to its stow position and the mirror stays in an almost vertical position until sunrise.

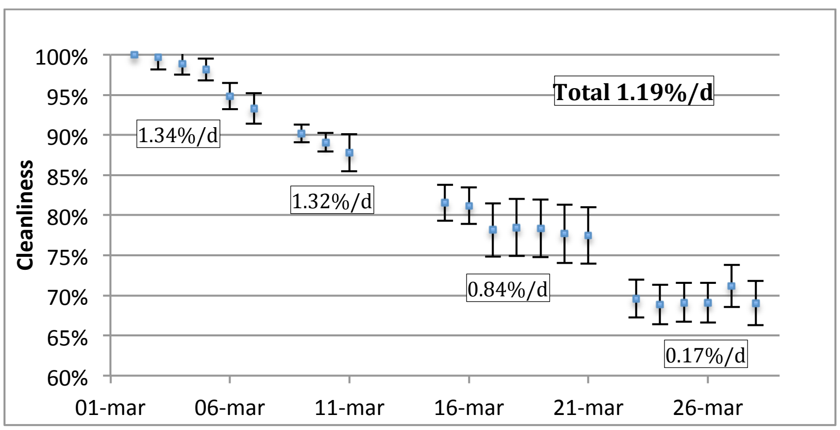


Figure 2-9: Cleanliness values for the month of March of the reference mirror installed in the TraCS.

Other important fact to notice from the results of the reference mirror is how the error increased with time. This is explained by the non-uniformity of soiling and the formation of packed cement-like composite caused by dew (see Figure 2-10).

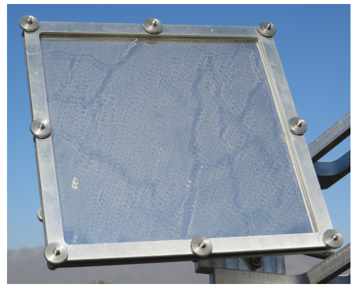


Figure 2-10: Reference mirror on the 15th of March. Non-uniform soiling can be noticed with traces of drop of water rolling down the surface.

On Table 2-2 a summary of the average soiling rates are presented. These values are the preliminary results of measurements in San Felipe. More test must be achieve for acquiring seasonal and annual values.

Table 2-2: Summary of average values of daily soling rate for each material.

Sample material	Minimum	Maximum	Average per week
Polymeric films	1.67%	2.68%	2.14%
Glass Mirror (sample)	0.68%	1.41%	1.16%
Glass Mirror (reference)	0.17%	1.34%	1.19%

2.4 Economic model

2.4.1 Methodology

A model is presented for calculating the optimal cleaning cycle of solar mirrors. This method finds the cost and cleaning frequency for different cleaning methods. The main input is the soiling rate of the plant that is dependent of the location of the project.

Soiling affects directly the reflectance of the reflective mirrors. The soiling rate is variable, because it not only depends on the climatic conditions of the location but also of seasonal variation and occasional events like rain, storms, dew, or others. The annual average reflectance (ρ_{avg}) is calculated by considering the reflectance that the mirrors recover after cleaning (ρ_c), the soiling rate (R_{soil}), and the number of cleaning per year (w) (Kattke & Vant-hull, 2012).

$$\rho_{avg} = \rho_C - \frac{R_{soil} \cdot \rho_0}{2 \cdot w} \tag{2-4}$$

The values R_{soil}, ρ_c and ρ_0 are constant. The initial reflectance (ρ_0) is dependant on the material to be used (monolithic, polymeric or aluminum mirrors). The clean reflectance (ρ_c) is dependent of the type of cleaning, however, for extending periods is important to consider possible corrosion or degradations of the surface.

Cleaning may take several days, so it's important to include the decrease on the reflectance of the mirrors while the other are still being cleaned. Equation (2-5) shows the cleaning time of each cycle.

$$t' = \frac{A}{x \cdot N \cdot v} \tag{2-5}$$

A is the effective area of the reflective surface of the solar plant (m^2), N is the number of cleaning units (trucks or machines), v is the cleaning speed of each unit (m^2/h) and x is the cleaning shift (12 or 24 hours). Therefore, the equation for the annual average reflectance would be as shown on Equation (2-6).

$$\rho_{avg} = \rho_c - \frac{R_{soil} \cdot \rho_0}{2 \cdot w} - \frac{R_{soil} \cdot \rho_0}{2} \cdot \frac{t'}{x} \tag{2-6}$$

From Equation (2-6), the cleaning frequency per year can be found. See Equation (2-7).

$$w = \frac{0,5 \cdot R_{soil} \cdot \rho_0}{\rho_c - \rho_{avg} - 0,5 \cdot R_{soil} \cdot \rho_0 \cdot {t'}/{x}} \tag{2-7}$$

Each cleaning method has its own associated costs, including manual labor and resource use. The annual cleaning cost (P_W) per square meter of reflective surface it's shown in Equation (2-8). L is the manual labor (man-hours/m^2) for the cleaning and also for maintenance, L_c is the cost of labor ($/man-hours), W is the required water for cleaning (l/m^2) and W_c is its costs ($/l), F is the fuel used (l/m^2) and F_c is its cost ($/l), w is the cleaning frequency per year, I is the equipment fix cost (investment), A is the effective reflective surface and δ is the time that the trucks can work before beings replace.

$$P_W = N \cdot \left[(L \cdot L_c + W \cdot W_c + F \cdot F_c) \cdot w + \frac{I}{A \cdot \delta} \right] \tag{2-8}$$

2.4.2 Data Input

As exemplary results for the proposed economic model, several inputs data are used. The data for the cleaning methods was handed by the developers of the technologies and also some information found in other studies (Fernández-García et al., 2013; He et al., 2011; Schell, 2011). See Table 2-3.

Table 2-3: Technical data for each cleaning method for solar mirrors.

	Brush trucks	Automatic robot	Manual cleaning
Technology	Flat and curve collectors	Flat collectors	Flat and curve collectors
Cleaning method	High pressure water and brush	Water and brush	Pressurized water and/or brush
Manual labor	1 per truck	1 for 10 robots	1-2 per unit
Water use	0.5 – 0.7 l/m^2	0.2-0.3 l/m^2	0.5 – 0.7 l/m^2
Fuel use	5 km/lt (diesel)	Electric (battery)	Electric (battery)
Cleaning speed	3450 m^2/hr.	30 m^2/hr.	500 m^2/hr.
Cleanliness	98%	97-98%	98%
Cost	460.000 USD	22.000 USD	1.000 USD

Measurements made in San Felipe, Chile (see Chapter 2.3) shown in Table 2-2 were considered for the model. For the results, five ranges of daily soiling rates where analyzed: 0 to 0.1% (minimum), 0.1 to 0.6% (low), 0.6 to 1.2% (medium), 1.2 to 2.0% (high) and 2.0 to 3.0% (extreme).

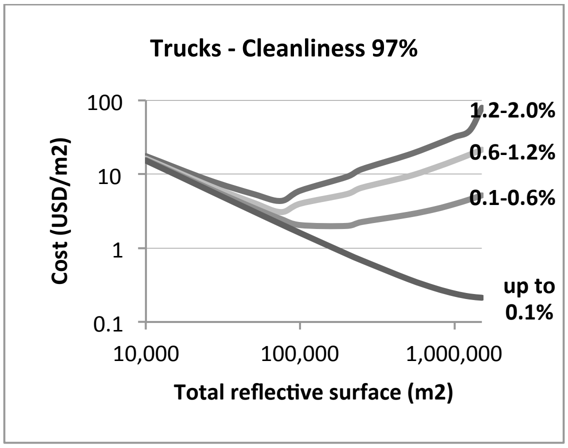
The price of water was calculated considering the data provided by reports published by the Superintendence of Health Services of the Government of Chile (Superintendencia de Servicios Sanitarios, 2016).

2.4.3 Results and discussion

2.4.3.1 Costs

Results where given without a specific material for the solar mirrors because the factor considered was the cleanliness goal. This is the average cleanliness that the plant maintains for its operation. For a mirror glass material, the initial reflectance is 95% so a cleanliness of 97% means an annual average reflectance of 92%.

For trucks cleaning method, the results are shown in Figure 2-11. A cleanliness of 97% and 95% is shown. Both results have the same graph structure, but the second is cheaper for an equal area. For small areas the difference is 5-10% more expensive but for big areas it can reach 60%.



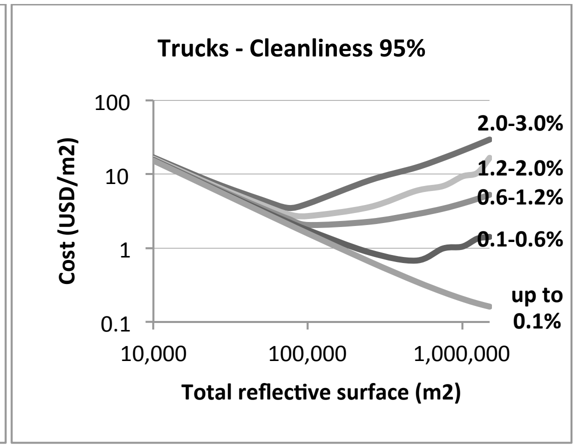


Figure 2-11: Cost of cleaning in USD per square meter for trucks cleaning method. Each curve indicates a range of soiling rate.

It is not feasible to use cleaning trucks for plants smaller than 10,000 m^2, because costs are extremely high and other methods can achieve better prices. The optimum field area depends on the soiling rate of the locations. For a soiling rate higher than 2% (extreme range) it is no possible to maintain the cleanliness on 97%.

Figure 2-12 shows the results for manual cleaning. Results show that this method is feasible for areas smaller than 50.000 m^2. For high and extreme soiling rate range the annual cost of cleaning is higher than 10 USD/m^2, which indicates that is an expensive method. A solution for decreasing the cost is reducing the cleanliness goal, which makes sense considering the high dust potential that those mirrors are exposed.

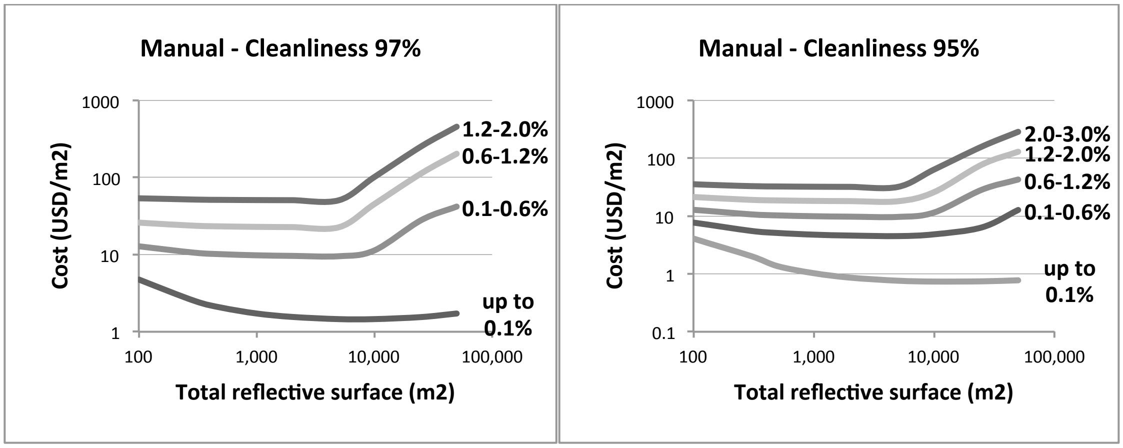


Figure 2-12: Cost of cleaning in USD per square meter for manual cleaning method. Each curve indicates a range of soiling rate.

Figure 2-13 shows the results for cleaning with automatic robots. This method is very expensive and is only feasible for areas around 10.000 m^2. Comparing to other methods, automatic robots will always be more expensive if normal inputs are considered. But it could be an interesting solution if innovation wants to be achieved and also if manual labor is extremely expensive.

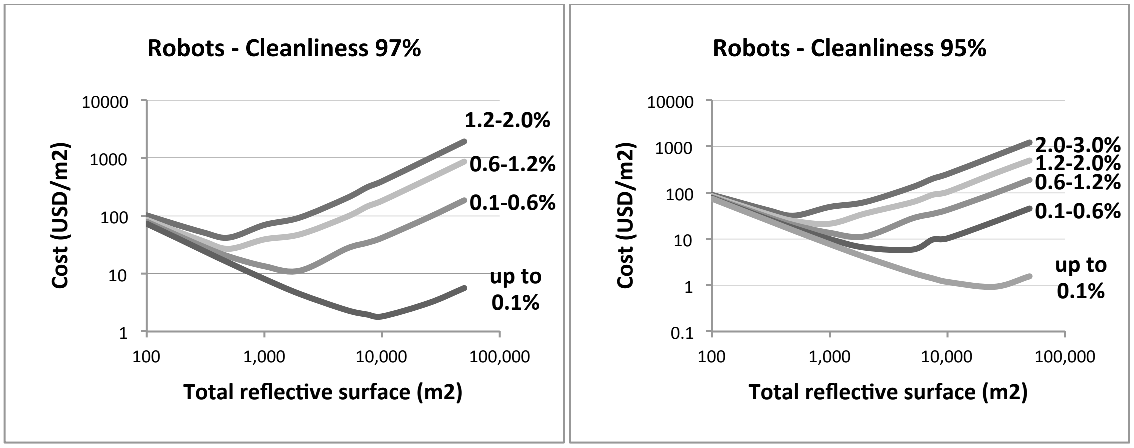


Figure 2-13: Cost of cleaning in USD per square meter for robots cleaning method. Each curve indicates a range of soiling rate.

As an example for cleaning cost trade off under this study, a plant of 200 MW was modeled for the Atacama Desert radiation. This central tower CSP plant considered a mirror surface of 1,300,000 m^2. The energy cost in USD per square meter was modeled in System Advisor Model (SAM) program for every annual reflectance (see Figure 2-14). The results indicate that increasing reflectance in 0.01 makes energy 1.4654 USD cheaper for every m^2.

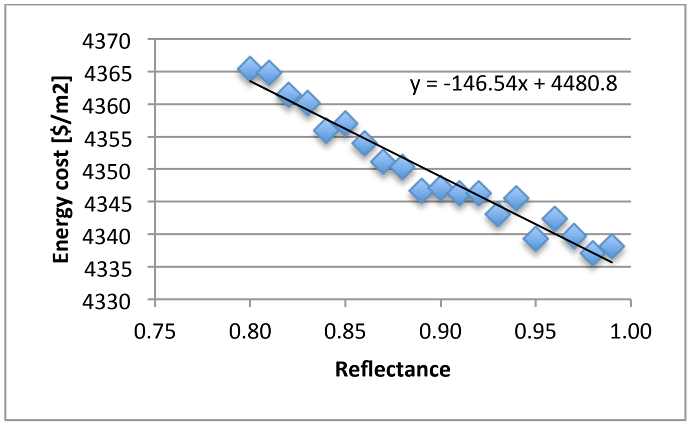


Figure 2-14: Results for SAM simulation of a 200 MW solar tower technology solar plant.

The SAM results indicate the performance gain for every change in reflectance. Energy costs are cheaper when reflectance is higher because more radiation is reflected to the receiver. This value gives a reference for limit cleaning cost; if the cost is higher than 1.47 USD it is not worth it to increase the reflectance.

2.4.3.2 Frequency

Other important factor in the results is the cleaning frequency. Results show that for maintaining the same cleanliness the frequency increase at higher soiling rate (See Table 2-4). In some cases, the frequency indicates that cleaning must be done almost every day (maintaining cleanliness in 97% and soiling rate of 2%).

Table 2-4: Frequency per month values for each cleaning method considering cleanliness of 97% and 95% for different soiling rates.

Cleanliness	Cleaning method	Plant surface	3%	2%	1,20%	0,60%	0,10%
97%	Trucks	10.000-500.0000	---	26,27	11,71	4,91	0,72
		500.000-1.500.000	---	26,27	11,71	7,25	1,01
	Robots	100-500	---	26,27	11,71	4,91	0,72
		2.000-50.000	---	26,27	11,71	7,25	1,04
	Manual	10-10.000	---	26,27	11,71	4,91	0,72
		10.000-50.000	---	26,27	11,71	7,25	0,89
95%	Trucks	10.000-500.0000	16,51	9,32	4,98	2,30	0,36
		500.000-1.500.000	16,51	7,41	7,41	4,22	0,46
	Robots	100-500	16,51	9,32	4,98	2,30	0,36
		2.000-50.000	16,51	13,44	7,41	4,22	0,61
	Manual	10-10.000	16,51	9,32	4,98	2,30	0,36
		10.000-50.000	16,51	13,44	7,41	3,30	0,40

These frequency values in some cases can be unfeasible, for the conditions of a particular project. Cleaning every day of a month could be possible for automatic robot where no manual labor is needed and water consumption is low, but for trucks this might not be optimal. Frequency could be reducing by considering more cleaning units or by redusing the cleanliness goal.

As a summary of the cost and frequency cycle, Table 2-5 and Table 2-6 were made in order to give general information for developers and maintenance managers. These results are a general range for costs, cleaning methods and frequency. Nevertheless it is important to make an individual study for each solar plant, dependent of its own restrictions of labor an resources cost, soiling rate, among others.

Table 2-5: Cleaning method recommendation for each range of solar thermal plant size.

Surface range	Power range	Cleaning method
0 – 10,000 m^2	Up to 1 MW	Manual cleaning
From 10,000 m^2	From 1 MW	Truck cleaning

Table 2-6: Optimal frequency and cost range for every range of solar thermal plant size for a cleanliness of 96%.

Surface range	Cost range	Optimal frequency
0 – 500 m^2	3 – 5 US$/m^2	1 per month
500 – 10,000 m^2	2 – 3 US$/m^2	1 per month
10,000 – 1,500,000 m^2	1 – 3 US$/m^2	1 – 2 per month
From 1,500,000 m^2	From 2 US$/m^2	1 – 2 per month

2.4.3.3 Cleaning technology map

As a resume of the results given by the economic model for calculating the optimal cleaning cycle, a graph was created for given an approximation of which is the optimal technology to use in maintenance of a solar plant. Figure 2-15 shows the results for a soiling rate of 0.6% and a maximum cleaning frequency of 2 per month. It can be observed that for small plants it is better to use manual cleaning and for bigger plants (10.000 m^2 or more) it starts to be more feasible to use more automatic methods (robots or trucks).

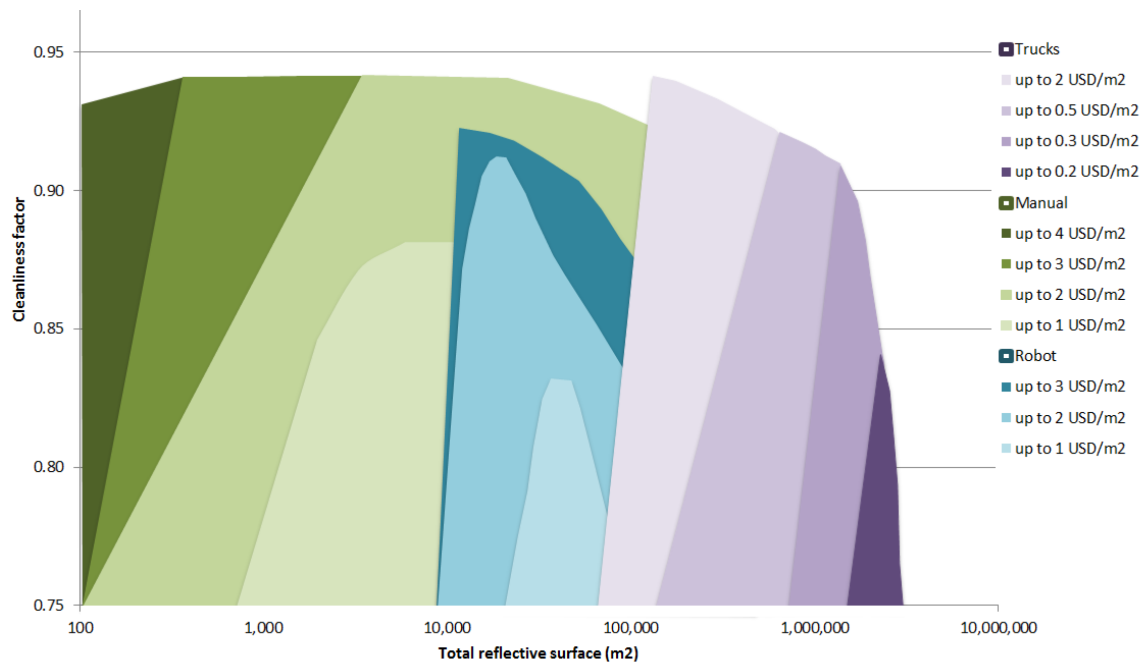


Figure 2-15: Cleaning technology map for a soiling rate of 0.6% (low medium range) and a cleaning frequency up to 2 per month.

As and example of the technology map, if a plant of 1,000 m^2 of reflective surface needs to maintain its cleanliness in 85%, the optimum cleaning method is manual cleaning with a cost lower than 2 USD per square meter. On the other side, for a plant of 1,000,000 m^2 that need to maintain its cleanliness in 90%, the optimum cleaning method is truck cleaning with a cost lower than 0.5 USD per square meter. If the plant is of 50,000 m^2 of reflective surface and need to maintain in 80% its reflectance, it is cheaper to clean manually, but also robot cleaning is an option. Robot cleaning is more expensive but it has several advantages such as minimum manual labor and it is a more innovative product.

Figure 2-16 shows the same map than before but for a soiling rate of 1.2% per day. This value is the upper limit of the medium range. For this value, cost increase considerably so for maintaining the cleaning frequency at 2 per month and low costs, the cleanliness goal must be lower than before. The highest value that it can be achieve is 0.88 for manual and truck, and 0.91 for automatic robots. If the cleanliness needs to be higher, the cleaning frequency can be increased.

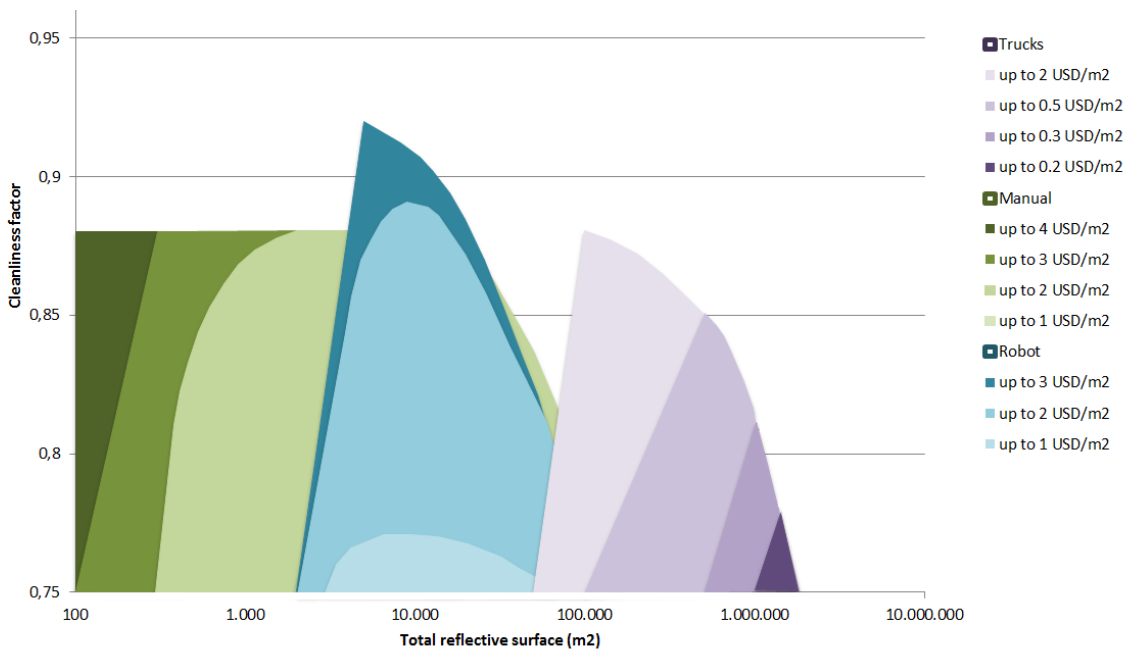


Figure 2-16: Cleaning technology map for a soiling rate of 1.2% (high medium range) and a cleaning frequency up to 2 per month.

The same simulation was made for a fix cost (lower than 2 USD/m^2) but no limit in the cleaning frequency. Results were the same for robot and manual cleaning. But for trucks, they gave the possibility of achieving higher cleanliness at prices lower than 2

USD/m^2 but higher cleaning frequency: 16 times per month for total reflective area higher than 500,000 m^2 achieving 94% of annual average cleanliness.

2.5 Conclusions

The first part of this paper is the soiling rate measurements in Central Chile. Mirrors of polymer films and monolithic glass were exposed for a month and measured on a weekly basis. Results gave important information related on soiling rates and also recommendations for future tests.

Soiling rates measured by the TraCS gave data under the high to extreme soiling range. The exposure bank was installed on north orientation with an inclination of 45º which made the dust deposited in the mirrors couldn't sled down the mirror. Usually thermo solar mirrors have rotational axes and during night they are places facing down or at 90º, which helps the dust to decrease. This information is important to realize that soiling rates measured in this test could be higher than the real rate that reflective mirrors of the solar plant have.

Other important conclusion of the test is the difference between both material exposed. Polymeric films soiled faster than mirror glass samples, which indicate that their soiling rate is higher (30% higher). Polymeric films are cheaper but their higher soiling potential indicates that the plant should have higher maintenance cost for achieving the same cleanliness than monolithic glass mirrors. For evaluating which material to use the trade off between material cost and maintenance cost must be considered.

The main goal for exposure test is to measure the soiling rate of the mirrors of the solar plants, so the exposure test should be similar to the mirrors set up. For future works, it is recommended to consider changing inclination, orientations and altitude of the measuring samples to achieve a more real simulation of the sun tracking mirrors of a solar thermal plant.

The second part of this paper was focus on the economic model for calculating the optimal cleaning cycle of a thermo solar plant. The model was illustrated as an example with data from San Felipe soiling measurements. This is a useful tool for project developers and maintenance operators to find the optimal cleaning technology and schedule, considering the particular restrictions of the plant: reflective surface, soiling rate, resource availability (water and fuel) and labor prices.

With the results it was revealed that maintaining a high reflectance in the field is expensive and there is a trade off between the frequency and cost depending on the soiling rate. Economic analysis find in references indicate that is cost-effective to maintain a cleanliness above 90% (Heimsath et al., 2010), but for knowing how much the plant can afford on maintenance an optimization between the cleaning cycle and the performance gain must be executed.

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