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# Effect of soiling and sunlight exposure on the performance ratio of photovoltaic technologies in Santiago, Chile

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ABSTRACT

The performance, yearly degradation, and annual yield of photovoltaic systems have been studied in outdoor exposure for two years period 2014–2015 in Santiago, capital of Chile. Photovoltaic panels performance degrades daily in a rate between −0.13% and −0.56% under soiling in highly polluted Santiago, Chile. Yearly degradation of the arrays system was found to be in the order of 1.29% for the polycrystalline array, 1.74% for the monocrystalline array, and 2.77% for the thin film system array. The annual production yield reached 1419–1373 kW h/kWp for Poly, 1459–1444 kW h/kWp for Mono, and 1248–1236 kW h/kWp for TF, in 2014 and 2015, respectively. The annual in-plane irradiation measured reached 1981.3 kW h/$m^2$ and 1943.2 kW h/$m^2$, for 2014 and 2015, respectively. A weather-corrected performance ratio is presented showing a yearly performance ratio of around 75% for all technologies. Monthly cleaning and random rain fall have shown positive effects as primarily solutions. Furthermore, we studied the optimal strategies of cleaning for different energy prices and we defined a critical cleaning period of 45 days for a real case, independent on cleaning cost and energy prices. This work contains novel results for the Chilean capital city and can be applied to future installations in the area and serve as further insights for the development of solar energy in Chile.


## 1. Introduction

Chile has become a promising country for photovoltaic (PV) plants installations since 2012. Following the growth of the electricity market, more than 0.74 GWp of Solar PV are under operation and around 2 GWp are under construction up to date [1]. Also, another motivation for PV worldwide is that the total cost of a fully installed utility PV system (fixed-tilt) is already below $1.5 per watt [2]. Although 80% of the performance is guaranteed by the solar panel manufacturer up to 25 years, the output power generated by a solar plant strongly depends on the climate parameters and the ambient aggressiveness of the specific field. Qualification of solar panels is the key for long term reliability, stability and guaranteed output power. Out in the field however, certified solar panels have shown failures mainly lying on interconnect breakage, solar cell cracks, and corrosion [3].

It is of paramount importance to follow a PV plant after installation in order to understand and characterize its failures in the field over long periods of time. Real conditions mean measuring the output power and *I–V* characteristics of solar panels under parallel incident radiation, recording the ambient and real module temperature together with the velocity of wind (speed and direction), and recording periods of cleaning and rain. A common drop on PV performance is produced by shadowing the incident sunlight due to soiling. Since the 80s it has been already known that testing PV panels under long periods of outdoor exposure is the most effective way to evaluate soiling [4].

Although the first PV plant in Chile began to operate in late 2012, solar energy research in Chile had previously started in the 60s. One of the first published works on Solar Energy in Chile was done on solar-heat collectors by Federico Santa Maria Technical University in Valparaiso [5]. The first solar radiation data was registered in Chile back to 1973, also by the same author [6]. After that, the solar energy resource data available in Chile was collected and published a few years ago on a review paper [7]. Later on, monthly means of radiation were published recently from satellite image available in Chile between 1995 and 2005 [8]. First studies on a panel prototype specifically designed for the Atacama desert have shown that glass to glass is a good solution for

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extremely high solar irradiation [9]. Furthermore, the Atacama Solar Platform project has started as an initiative for research of solar energy in north Chile [10]. Finally, the levelized cost of energy (LCoE) [11] and the performance of various solar panels have been analyzed in northern Chile showing the detrimental effects of high temperature on the performance ratio [12].

This work focuses on the soiling analysis for a PV grid-connected plant installed in Santiago Chile, where pollution and dust are heavily present and are a main problem during cold seasons. We select an optimal period for the analysis of two years. Irradiation and performance of different PV technologies are presented for this period. Also the yearly degradation of our PV system is discussed under real conditions as soiling, rain and shadowing. From our knowledge, this is the first time the performance of crystalline and thin film PV arrays are compared for two years period in Chile, where the effect of soiling and regular periods of cleaning on the non-corrected and weather-corrected performance ratio are presented.

## 2. State of the art: soiling and degradation

### 2.1. Soiling

Natural dust (soil) is a contamination source for PV panels mainly formed by airborne particulates. Soiling is the effect of particles deposition during a period of time where no external cleaning is present. The size of dust particles may vary from 1 μm to 500 μm, depending on the source. Particles from an industrial source include concrete, fibreglass, carbon fibres, brick among others, and particles from anthropomorphic pollution causing health risks (10 μm). If high relative humidity is present, the stickiness of soiling particles on the PV panel will increase and the effect of cleaning by wind will be reduced. In other words, low moisture present in the particles influences on a suspension by wind [13].

The electrical performance of the PV panel is strongly affected by partially shadowing the front surface module glass due to particle deposition. The main factor is that particles of soiling can behave as dielectrics, absorbing incident light and reducing transmission or even produce reflection by changing the angle of incidence of light into the module. It has been shown that the performance degradation of solar panels can range from 2% to 60% power loss, depending on time and site of particle accumulation, and that the effectiveness of cleaning by rain heavily depends on material properties [4].

Although soiling is not standardized as a PV module failure [14], its detrimental effect on reducing the electrical output of Photovoltaic (PV) solar panels is well known. PV panel performance has been compared before and after cleaning [15]. Particles present in soiling are normally water-soluble, so that a short cleaning process is sufficient to remove the coating from the surface and bring the panels to original state. However, in some desertic areas, cleaning by water is no sufficient and chemicals have to be added to the mixture to improve cleaning and water saving [16]. After a very dry period some particles are resistant and sequential cleaning procedure is needed. Thus, the effectiveness of cleaning by rain depends on the amount of rain and the humidity present in the day.

Several studies can be found worldwide, and depending on the location site the electrical performance degradation has different rates. In Europe, the mean daily production losses in Malaga (Spain) caused by the accumulation of dust deposited on the surface of the PV module was around 4.4% and in long dry periods of dust accumulation this value was higher than 20% [17]. In Belgium, the power loss was between 3% and 4% in a period of 5 weeks [18]. In Crete, the annual soiling losses were estimated to be 5.86% [19]. In the countryside of Southern Italy a 6.9% and 1.1% monthly power losses were found for a plant built on a sandy soil and a plant built on a more compact soil, respectively [20]. In Gran Canary Island, relative efficiencies dropped to 20% of the initial values within 5 months, and recovered their initial value after rainfall [21]. In Kuwait, soiling losses amounted 45.8% over three months period without cleaning [22]. In California, soiling losses averaged 0.051% per day of conversion efficiency during dry seasons [23] and 7% annually [24]. In Brazil, the chemical properties of soiling particles are primary silicates critical for the adhesion [25]. In the Atacama Desert (Chile), PR decreased at a rate of 4.8%/month for thin film technology and at a rate of 6.2%/month for multicrystalline, due to the dust accumulation and extreme temperatures [11], although none weather-correction of the data has been performed so far in Chile [26].

The pollution coming from nearby highways or cities is a critical factor influencing soiling and cleaning [27]. The detrimental effects of hydrocarbon fuels enhanced the bonding of soiling particles to the surface; soiling properties related to Na, Mg, and Cl have been reported from near traffic highway [25]. In Santiago, Chile, the pollution is heavily present [28]. Although we have not yet performed chemically analysis of the soil present on our modules in Santiago, nevertheless, the soiling losses can be directly related to the polluted air from urban and industrial environment, since our plant is installed close to heavily trafficked roads.

All this studies show that it is indeed worth focussing on preventing soiling or developing anti-soiling technologies.

Nowadays there are methods developed from different authors which are trying to predict soiling effects [20,29–33], showing the benefits in terms of revenues for the PV industry. Besides this, anti-soiling techniques have been developed as self-cleaning glazing products [34] and anti-soiling photocatalytic coating [35].

### 2.2. Degradation

Panel degradation occurs directly after light exposure. Rapid initial degradation correlates to oxygen contamination in the silicon material and long time degradation is attributed to long ultraviolet exposure [36]. Both, crystalline and thin film technologies suffer directly after light soaking: For crystalline, this phenomena is known as light induced degradation (LID); For thin film technology, the process occurs faster than in crystalline due to defects and vacancies in the amorphous material. This light induced phenomena is also known as Staebler Wronski Effect (SWE), which describes the decrease of photoconductivity of the solar cells based on a-Si [37]. Another degradation of solar panels can be found depending on many factors, from solar cell and manufacturing procedures, to PV plant electrical design and polarization of panels. This phenomena is called potential induced degradation (PID): at the cell level, parasitic positive charges can approach to the cell due to sodium diffusion from encapsulant to the cell [38]; at the PV plant level, wrong electrical configuration of the whole system may produce negative potential relative to earth. Thus, PID can be avoided by hard grounding the inverter/transformer to earth or soft grounding the transformerless inverter. Also, humidity and temperature have been shown as a detrimental effect to increase PID [39]. Furthermore, delamination and discoloration has been in deserting climates zones [40].

Degradation rates of solar panels can change for different climate conditions. It has been shown that these rates can vary from 0.17%/year in Sweden to more than 0.5%/year in USA [36]. Most of failures lie on interconnect breakage, solar cell cracks, and corrosion [3], although electrical solar cell parameters can be affected due to a lack of high quality processing. A correct degradation analysis needs to cover a long period of time above at least 2 years [15,36], and should be performed comparing $I$–$V$ data before and after this period of time. Since this analysis is difficult to perform, most of the time, degradations are reported taking into consideration the performance ratio and not the *I–V* characteristic of solar panels [41].

Our results can give further insights on the particular influence of the climate conditions on the degradation rates of PV technology in Chile.

## 3. Performance ratio of PV panels

The standard test conditions (STC) of a solar panel describe their performance under perfect unreal conditions at laboratory level (under 1000 W/m$^2$ at 25 °C). However, in real conditions solar panels are installed under direct sunlight where high irradiation is present as well as extreme high ultraviolet values. In order to analyze PV plants in rear conditions, the performance ratio (PR) is used as a quality factor.

Through the PR solar PV panels can be compared independently of their STC parameters, location, irradiance conditions, orientation and tilt angle [42]. However, PR highly depends on weather conditions [26]. Practically, PR is the efficiency of a solar panel in a specific place after losses. Therefore, standardized performance ratios have been introduced as a more reliable parameter for characterization of solar plants [42]. PR mainly depends on the temperature of the module, power dissipation, measuring system, and dust or particle contamination from pollution [43], also known as soiling. Other operational parameters such as the efficiency of electrical connections and power outage, may influence further the data collection and PR values. Also, the normal yearly degradation of the PV panels impacts the PR; usually less than 0.5% yearly degradation is expected in similar climate conditions [44]. As shown by Eq. (1), PR compares the final output yield of the PV array, $Y_F$, to the reference (or theoretical) yield of the plant, $Y_R$ (according to [45]). $Y_F$ is also known as the full load hours of the plant, or the measurable time at peak power a PV plant needs to operate to produce the energy output under the current real conditions. Thus, it depends on the solar irradiation and it is defined as the ratio between the Panel Output Energy, $E_{AC}$, and the Peak Power in STC, $P_{STC}$. The main detrimental factors on PR are the losses due to soiling but also due to shadowing, electrical installation losses, yearly module degradation, and losses due to angular and spectral reflectance.

$$PR = \frac{Y_F}{Y_R} = \frac{E_{AC}}{P_{STC}\frac{POA}{H_{STC}}} \quad (1)$$

$Y_R$ is known as the number of peak sun-hours and defines the irradiance perpendicular to the plane of array (*POA*), normalized to the reference irradiance in STC, $H_{STC}$. Since PR is normalized to the solar irradiation its value is less influenced by weather conditions, but it still presents weather variability, such as sensitivity in changes of temperature or wind [20,46].

The standard PR represents the actual performance of the PV plant. We will use it to describe the plant performance all over the studied period. Nevertheless, in order to study the influence of soiling and degradation in a certain location, it becomes essential to remove the effects of weather variables (temperature and wind) on the PR. Therefore, we apply a weather correction model to our data.

### 3.1. Weather-corrected performance ratio

It has been shown that the PR data presented so far highly depends on PV system efficiency and weather conditions (in this case Santiago, Chile). The results vary from summer to winter due to the variations in atmospheric conditions. A weather-corrected PR has been introduced by the National Renewable Energy Laboratory (NREL) [26], which reflects a consistent seasonal value for PR in a specific place for any PV technology. This value has a bigger industrial impact than the non-corrected PR, which can vary −0.9% if baseline temperature increases 3 °C further and 1.7% if baseline wind speed increases 3 m/s [26]. Eq. (2) shows the weather-corrected PR as presented by NREL [26]:

$$PR_{corr} = \frac{E_{AC}}{P_{STC}\frac{POA}{H_{STC}}\left(1 - \frac{\delta}{100}\left(T_{cell-avg} - T_{cell}\right)\right)}, \quad (2)$$

where $\delta$ is the temperature coefficient in $P_{mpp}$ for each PV technology, $T_{cell-avg}$ is the average calculated cell temperature from one year and $T_{cell}$ is the calculated cell temperature. Using this formula we corrected our PR data for each technology as shown in Fig. 5.

## 4. Experimental setup

This study was performed on an open rack type PV system located at the Pontifical Catholic University of Chile. The data collection started in December 2013. It is located at a latitude 33.50°S, longitude 70.61°W, and altitude 577 m. The tilt angle of the panels was 32° and the azimut, 350° (pointing North but shifted 10° towards the West).

Fig. 1 shows the PV plant for the study, containing grid-connected PV systems, climate sensors, and pyranometers needed for solar panel quality control and solar resource assessment. We analyzed market available PV technologies based on monocrystalline silicon (Mono c-Si), polycrystalline silicon (Poly c-Si) and thin film (TF) PV technology.

These systems are installed at the roof of a three floor building and their characteristics are detailed in Table 1. Although c-Si PV is the prevalent technology, with more than 90% market share compared to TF with 5%, it makes sense to compare all technologies because they differ from temperature coefficient ($T_{Coeff}$) and from maximum output power per area installed, W$_p$/m$^2$. The thermal coefficient gives the derivative between the electrical solar panel parameters and temperature and they are determined experimentally. In indoor conditions, an A flasher excites the PV panel up to 1000 W/m$^2$, measuring *I–V* characteristics after heating the panel in a range of temperatures. In our case, we show the temperature coefficient for the maximum power, $T_{Coeff}$ $P_{mpp}$, which is the product of the current $I_{mpp}$ and voltage $V_{mpp}$ in maximum point, both depending on irradiance and temperature [47]. Furthermore, the number of panels in series connected per array (N°) was selected accordingly to make the three arrays comparable in size (maximum output power, $P_{STC}$(W$_p$)). The calculated maximum output power per unit of area installed (W$_p$/m$^2$) is used to differentiate technologies; for the same installed surface, the Mono PV array will produce more than 2.3 times the output power of the TF PV panels and 1.1 more than the Poly PV panels.

The PV system was monitored from December 2013 to November 2015, which means a period of 24 months. A meteorological station was installed next to the grid-connected PV to measure wind direction, wind speed, temperature, rain, relative humidity, direct normal, diffuse and global irradiance. To simulate the benefits of an industrial cleaning process, the PV systems were cleaned sequentially. In a similar way, the raining events were recorded during a period of 18 months.

In this work, the PV system has been cleaned monthly by brushing with water during the two years in this study.

### 4.1. Data collection of irradiance and meteorological parameters

Planning PV plants requires estimating in an accurate manner the total power output by performing a solar energy assessment.

**Fig. 1.** PV Plant showing climate sensors and PV arrays of mono-, polycrystalline and thin films solar panels.

**Table 1**
Three PV arrays under analysis and their respective temperature coefficients for maximum operation power, and maximum power at STC.

| Name | Technology | N° | $T_{Coeff}$ for $P_{mpp}$ | $P_{STC}$ ($W_p$) | $W_p/m^2$ |
|---|---|---|---|---|---|
| TF | a-Si/μc-Si | 12 | −0.33%/K | 1380 | 57.5 |
| Poly | mc-Si | 6 | −0.44%/K | 1410 | 117.5 |
| Mono | Cz–Si | 6 | −0.44%/K | 1590 | 132.5 |

The incoming data from the sensors was stored in a the Campbell Scientific CR1000 datalogger. This device collects the data taking averages of irradiation and ambient temperature every 1 min. The datalogger uncertainty lies by ±0.06% of reading plus offset. The maintenance of the sensors was carried out every other day. Our measurements are in accordance with the guidelines of the standards for regulation of PV measurements (IEC 61724 [45]).

*4.1.1. Measurement of irradiance*

The global horizontal irradiance (*GHI*), which is the geometric sum of the direct normal irradiance (DNI) and the diffuse horizontal irradiance (*DIF*), was measured by a CMP21 Kipp and Zonen pyranometer. The *DIF* was also measured with a CMP21 Kipp and Zonen pyranometer including a full globe shadowing, having the same accuracy. The DNI was measured with a CHP1 Kipp and Zonen, with also a ±2% of accuracy. The tilted direct irradiance was obtained after applying the model presented by Gulin et al. [48]. Then, the tilted diffuse irradiance was calculated by the Klucher model [49], which considers that the diffuse irradiance is not isotropically distributed over the sky dome. Afterwards, tilted reflected irradiance (albedo) was calculated assuming that the ground reflection process is ideally isotropic [48], which means that a constant irradiance is originated from every point of the ground. Finally, adding all the tilted components it is possible to obtain the global irradiance on the plane of array, *POA*. Our devices have been calibrated and installed on the tilted panels at 32°, having an accuracy better than 5% of the reading.

*4.1.2. Measurement of ambient air temperature and relative humidity*

The sensors were installed near to the PV plant to make the measurement representative of the array. A CS215 Campbell was used to measure the ambient air temperature and the relative humidity with an accuracy of ±0.4 °C and ±2% (range 10–90%) or ±4% (range 0–100%), respectively.

*4.1.3. Measurement of wind velocity*

The wind speed and direction were measured by an ultrasonic anemometer Young 85,000 at an altitude of two meters over the surface of the PV plant, having an accuracy of ±2% for speeds between 0 and 30 m/s (or 0.1 m/s), and ±3% for the range of 30–70 m/s, whereas the accuracy in direction was ±2°.

*4.1.4. Measurement of rain*

The rain amount was compared to the station La Platina INIA[1] located at latitude 33.34°S, longitude 70.37°W, and altitude 631 m, obtaining a good agreement between both data.

*4.1.5. Measurement of module temperature*

The module temperature was measured by means of a PT100 temperature sensor connected directly to the back sheet.

## 5. Results and discussion

This section is divided into several subsections. Firstly, Section 5.1 shows the records of two years of global irradiation in Santiago, both horizontally and in the *POA*, as well as the yield of the PV plants. Besides, some particular working conditions are presented, focusing on the cell temperature reached. Then, the daily PR is depicted in Section 5.2 for all technologies for the whole period studied. Later on, Section 5.3 details the results for soiling and degradation, based on the weather-corrected PR. Finally, Section 5.4 gives some insight in the economical implications of soiling.

*5.1. Solar and energy yield assessment*

Fig. 2 depicts the daily averages of irradiation, expressed in terms of global horizontal and in the *POA*, measured during 2 years in Santiago (Chile) by our devices between December 2013 and November 2015. As well, it is represented the accumulated yield, $Y_A$, from the beginning of the installation up to 2 years. Remarkable is the value for the irradiation *POA*, lower in summer but higher in winter, compared to the *GHI*. This shows that a perfect system would be a tracking one, where the tilted angle of the array were changed during cold or hot seasons. As well, it is outstanding the high level of daily irradiation recorded in Santiago, which can be

[1] Website: http://agromet.inia.cl/estaciones.php.

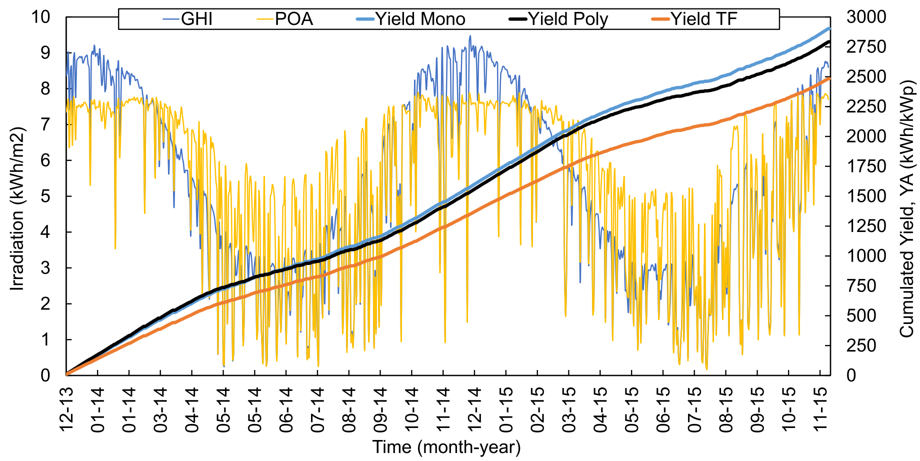


**Fig. 2.** Two years data for global irradiation *POA* and *GHI* in Santiago (Chile) and cumulated final yield of array, $Y_A$, for all PV technologies. 32° tilt angle and 350° azimut, shifted 10° towards the West.

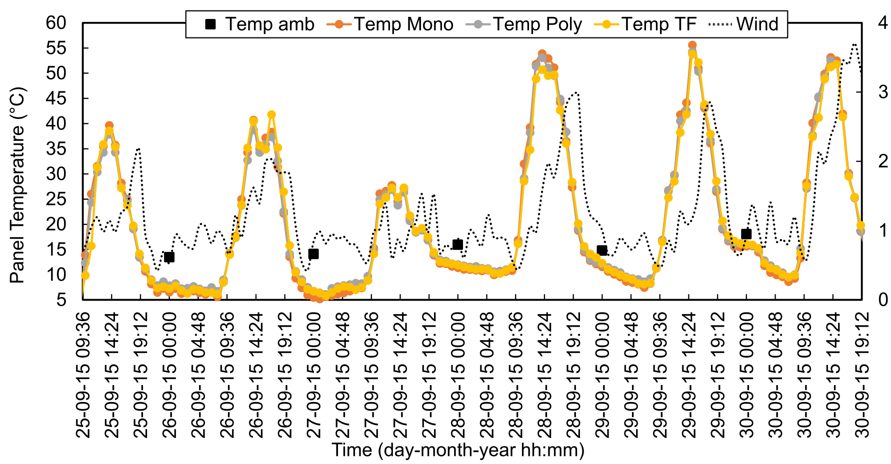


**Fig. 3.** Temperature of solar panels and wind speed for 6 days of analysis.

as high as 9.5 kW h/m$^2$. The annual *POA* irradiation reached a value of 1981.3 kW h/m$^2$ and of 1943.2 kW h/m$^2$ in the first and second year, respectively. *DIF* was evaluated to be 509.3 kW h/m$^2$ and 548.36 kW h/m$^2$, in the first and second year, respectively.

The cumulative annual energy yield of array $Y_A$, represents the energy production per rated peak Watt and is calculated and analyzed for comparing technologies over a long period of time [50]. It represents the cumulated sum of daily energy output of the PV array, $E_{AC}$, divided by the nominal power, $P_{STC}$. Different slopes can be appreciated in the accumulated yield curves, corresponding to the winter and summer months. The annual yields reached the following values the first and second year, respectively: 1248–1236 kW h/kWp for TF, 1419–1373 kW h/kWp for Poly, and 1459–1444 kW h/kWp for Mono.

The variation from first to second year reached 1% for TF and Mono technologies, whereas for Poly its yield decreased from the first to the second year in 3.2%. The difference between both crystalline arrays was pronounced during the cold winter season of 2015. In the first year the final energy yield of both crystalline arrays was similar, thus, they were comparable in performance, and only at the end of 2015 a variation of 2% was found maybe related to system and shadowing losses.

#### 5.1.1. Influence of weather variables on solar panel temperature

The panel temperature measured on the back changed with the ambient temperature, direct irradiation and wind speed. Fig. 3 resumes the panel and ambient temperatures under outdoor exposure for all PV technologies against wind speed for a period of 6 days in Spring season (25-09-15 to 30-09-15; Summer data is not available yet). The PV array temperatures presented similar tendency for all technologies. However, TF panels remained at lower temperatures (i.e. during peak hours on 28th September 2015). This was due to the fact that TF have a different structure and a lower thermal coefficient than crystalline. The maximum temperature reached values up to 55 °C by 15:00. Furthermore, between 11:00 and 20:00 the panel temperatures were higher than ambient temperature. Wind influenced on decreasing surface temperature and, therefore, the measured averaged temperature in the panel decreased when wind speed increased: late in the afternoon, by 18:00, values up to 3 m/s were registered in the installed PV plant. On 27th of September 2015, panel temperatures were remarkably lower compared to previous days due to a low irradiation levels – *POA* of 1.9 kW h/m$^2$, compared to a maximum value in the same week of 6.1 kW h/m$^2$ on 30th of September 2015. Thus, irradiation and wind have to be taken into account to understand the performance of PV panels under outdoor conditions. At this extent, out in the field, *I–V* tracers calibrate the collected data from PV arrays to the irradiation *POA* and panel temperature to obtain an adequate short circuit current, $J_{SC}$.

### 5.2. Daily performance ratio of PV arrays

PR was calculated from the *GHI* and power output obtained from our PV arrays for 24 months of analysis and is shown for each technology as presented in Fig. 4. The panels were cleaned monthly, as pointed by the vertical solid lines, to simulate the benefits of an industrial cleaning process. Besides, the random rainy days over 0.3 mm are shown in vertical dotted lines as guide-to-the-eye. Values of PR exceeding 100% are possible in short intervals of time due to high irradiation and low temperatures, but were not presented.

A first look on the graphs brings the following discussions. Firstly, a clear daily decay of PR due to soiling is present until cleaning is performed on the panel's surface or rain occurs. Soiling will be further analyzed in Section 5.3. Secondly, PR highly depends on the ambient temperature (and therefore on panel temperature) in an inversely proportional manner. Winter months presented the highest PRs, with mean values up to 0.85 for both

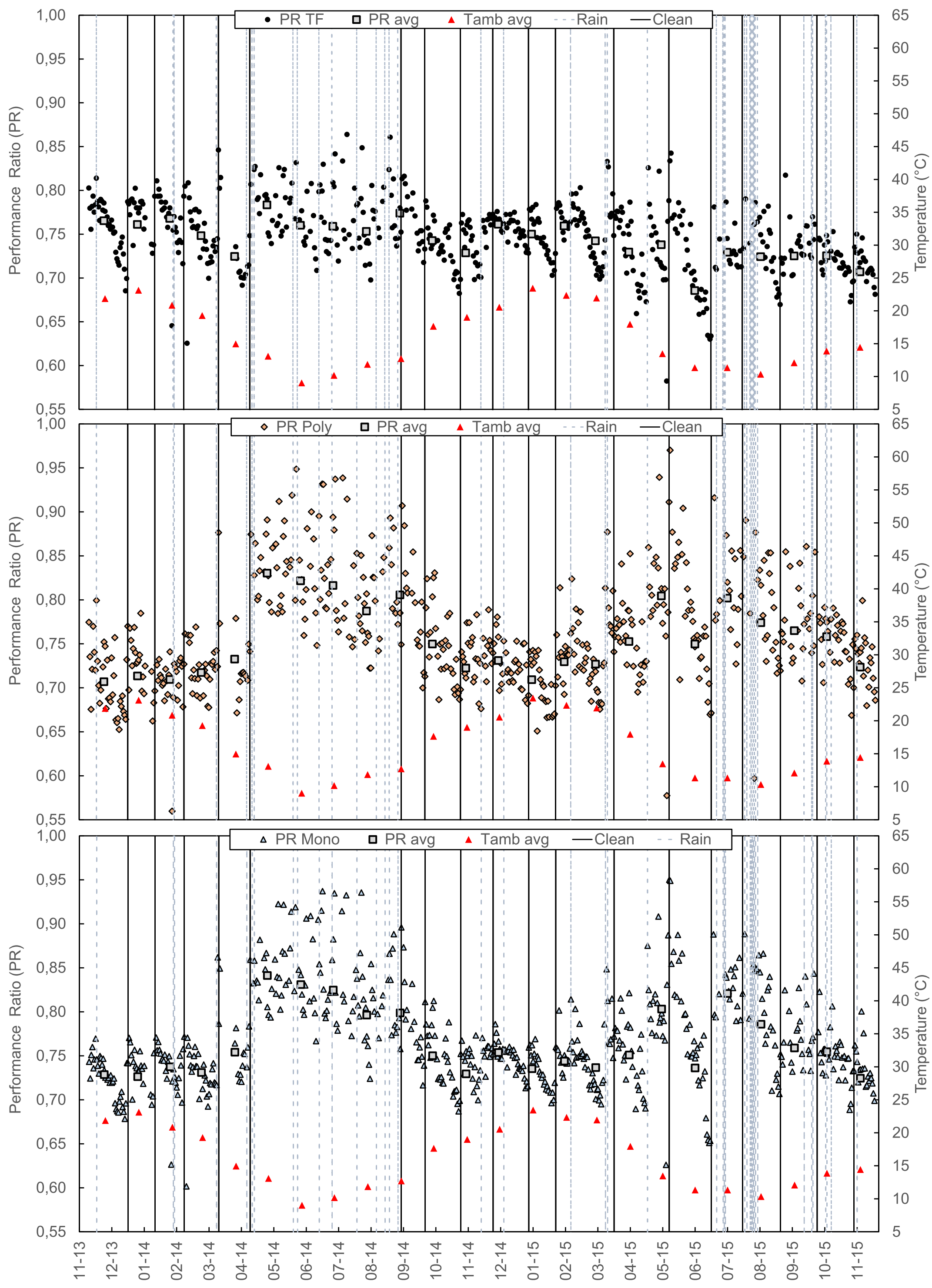


**Fig. 4.** Average daily and monthly PR for TF, Poly, and Mono PV arrays and average monthly ambient temperature $T_{amb}$, measured within two years period: December 2013 – November 2015. Monthly cleaning and rainy days are shown in full and dashed vertical lines, respectively. The time line is shown in the bottom x-axis in month-year format.

crystalline technologies. The TF arrays, due to a lower temperature coefficient, presented lower values of PR during winter and higher in summer months than their neighbor technologies (i.e. during first summer, where TF averaged above 0.75). As well, this technology is more affected to incident spectra (low irradiance values and low incidence angles) compared to crystalline [36]. Thus, TF is less affected by temperature and a weather-correction on PR will show less effect than on crystalline technologies. Finally, a remarkable dispersion of data was found in winter in comparison to summer, when temperatures and direct irradiance are lower and higher diffusivity of incoming light, as well as rain, are present. This effect is more notorious during winter 2014 (06–14 to 08–14) than in winter 2015 (06–15 to 08–15), when monthly cleaning was performed. Standard deviations of PR ranged ±3.39 to ±7.17 in winter depending on the technology. However, those values were reduced to ±1.64 to ±4.61 during summer months. Spring and autumn occupied intermediate values. Besides, dispersion of PR values was greater for the Poly technology than for the other PV systems, due to some shadowing issues present in the construction.

As shown in Fig. 4, data dispersion in summer was low for all technologies. Their values are resumed in Table 2: monthly PR averages ranged 76.47–75.69% for TF, 70.98–72.32% for Poly, and 73.07–74.43% for Mono, in summer 2014 and 2015, respectively. In winter, PR increased due temperature variation, reaching values of 75.74–71.30% for TF, 80.83–77.51% for Poly, and 81.73–78.09% for Mono. The difference for TF was not enhanced from summer to winter as compared to crystalline, due to their specific properties as discussed above.

### 5.3. Soiling and degradation of PV arrays

This section presents two paramount detrimental effects on PV performance: soiling, presented in Section 5.3.1 and degradation, presented in Section 5.3.2.

Since weather variables – mainly temperature and wind – have an influence on PR, those effects should be removed before assessing the consequences of soiling or degradation on PR in a fair way. As pointed in Section 3.1, an increase of 3 °C in the baseline temperature would make PR vary −0.9%, which could mask the effects of soiling or degradation. Thus, we applied to our collected data a weather-correction model, as suggested by [26].

#### 5.3.1. Soiling effect on PV performance

Fig. 5 shows the PRs for each technology after applying the weather correction. As shown, PR variability was reduced compared to Fig. 4, flattening extreme values, but still presents some variation. Seasonal variations after weather correction were also observed by [41], which suggests that there are other variables, apart from temperature and wind, that affect module performance, as for example spectral changes in irradiance. The effects of soiling can be easily observed in Fig. 4, resulting in a clear daily decay between cleaning periods. Results show that, specially in cold seasons, rain in Santiago was effective for cleaning the solar panels. During winter 2014, with many well distributed rainy days, no soiling could be appreciated. Nevertheless, in winter 2015, with rainy periods more separated in time, strong soiling losses could be observed. Table 2 shows the main results of the analysis of this paper. It resumes the seasonal average performance of the PV arrays and the effects of soiling. The calculated PR (from Fig. 4) and weather-corrected PR (PR corr, from Fig. 5) are presented, as well as the average daily decay due to soiling.

Normally, lowest decay values were obtained in summer 2015, with a daily slope of −0.14%, whereas highest values were found on autumn 2015, reaching a seasonal average of −0.56%/day for the TF technology, which means a monthly decay of 17.36% in the PR. The worsening of the PR found in the studied installation is greater than some reported by [18,23,20,11], but in the same range as [22] (approximately 15.26%/month).

It can be explained by the high levels of pollution present in the air, since the PV plant is located close to an urban and industrial area. Similar results were found elsewhere [27].

#### 5.3.2. Degradation of PV panels

Yearly degradation of solar panels should be calculated after many years of installation, since degradation rates are in the order of 1% and the measurement equipments present similar uncertainties. Despite our plant being installed 2 years ago, it is still possible to have an insight in the performance degradation [51]. Table 3 shows the yearly corrected PR and the positive (array-level) degradation for all the PV technologies within 2 years. The crystalline arrays had the biggest PR dispersion due to a higher temperature coefficient, with a standard deviation approximated to ±3.0% in 2015. As observed, during 2014, all technologies obtained similar PR, and our results are comparable to those reported by NREL [36].

These degradation values include the degradation of the whole system in a period of 2 years, and are usually called array-level degradation. As shown elsewhere, a median of 0.5% degradation (for crystalline and thin film) can be found for a period of study above 10 [36] to 20 years [52]. In our case, the Mono array system presented higher yearly degradation in performance than Poly, which is comparable to the results found by AIST in Japan under real conditions [53]. On the other side, TF array system experienced the biggest drop in performance from all study, up to 2.77%. These values are of paramount importance: it means the output power will be penalized and less cash will flow to the owner [54]. However, since our system was installed late in 2013, the degradation rates presented include the usually high panel degradation from the first year. Thus, the studied system should be stabilized after 2 years of operation. Panel manufacturers warranty covers 10 years at 90% performance guarantee and

**Table 2**
PR results in seasons (corrected and uncorrected) for all PV technologies between 2014 and 2015 in Santiago (Chile). $T_{amb}$ is the seasonal average. The effect of soiling is represented by the PR daily decays, shown as average for each season.

| Season | 2014 | | | | 2015 | | | |
|---|---|---|---|---|---|---|---|---|
| | *Sum* | *Aut* | *Win* | *Spr* | *Sum* | *Aut* | *Win* | *Spr* |
| $T_{amb}$ (°C) | 21.95 | 15.77 | 10.35 | 16.42 | 22.12 | 17.79 | 11.25 | 15.34 |
| PR TF (%) | 76.47 | 75.20 | 75.74 | 74.84 | 75.69 | 73.66 | 71.30 | 71.91 |
| PR TF corr (%) | 77.62 | 74.92 | 74.09 | 74.62 | 76.79 | 73.35 | 68.94 | 71.08 |
| Avg. decay (%/day) | −0.24 | −0.25 | – | −0.32 | −0.14 | −0.56 | −0.2 | −0.15 |
| PR Poly (%) | 70.98 | 76.00 | 80.83 | 75.92 | 72.32 | 76.12 | 77.51 | 74.87 |
| PR Poly corr (%) | 72.80 | 75.49 | 77.93 | 75.71 | 74.01 | 75.53 | 73.53 | 73.73 |
| Avg. decay (%/day) | −0.17 | −0.15 | – | −0.28 | −0.13 | −0.41 | −0.24 | −0.21 |
| PR Mono (%) | 73.07 | 77.54 | 81.73 | 75.94 | 74.43 | 76.35 | 78.09 | 74.60 |
| PR Mono corr (%) | 74.78 | 77.08 | 79.08 | 75.72 | 76.01 | 75.76 | 74.48 | 73.45 |
| Avg. decay (%/day) | −0.20 | −0.15 | – | −0.28 | −0.13 | −0.43 | −0.31 | −0.15 |

25 years at 80%. It means, a degradation rate of around 1%/year occurs the first 10 years, which is much less than the system degradation found here. It is then of paramount importance to understand the influence of climate conditions of a specific place on panel performance and system warranty.

In the case of a-Si TF PV technology, it is known, that a drop in the order of 1% [36] in panel power output can directly be

**Table 3**
Yearly PR [%] (average of monthly values) for each technology with the standard deviation and degradation of the PR during the studied period. *Diff.* states for the difference between PR in year 2014 and 2015.

| Year | *TF* | *Poly* | *Mono* |
|---|---|---|---|
| 2014 | 75.31 ± 1.86 | 75.49 ± 2.96 | 76.66 ± 2.68 |
| 2015 | 72.54 ± 2.14 | 74.20 ± 3.04 | 74.92 ± 2.95 |
| *Diff.* | 2.77 | 1.29 | 1.74 |

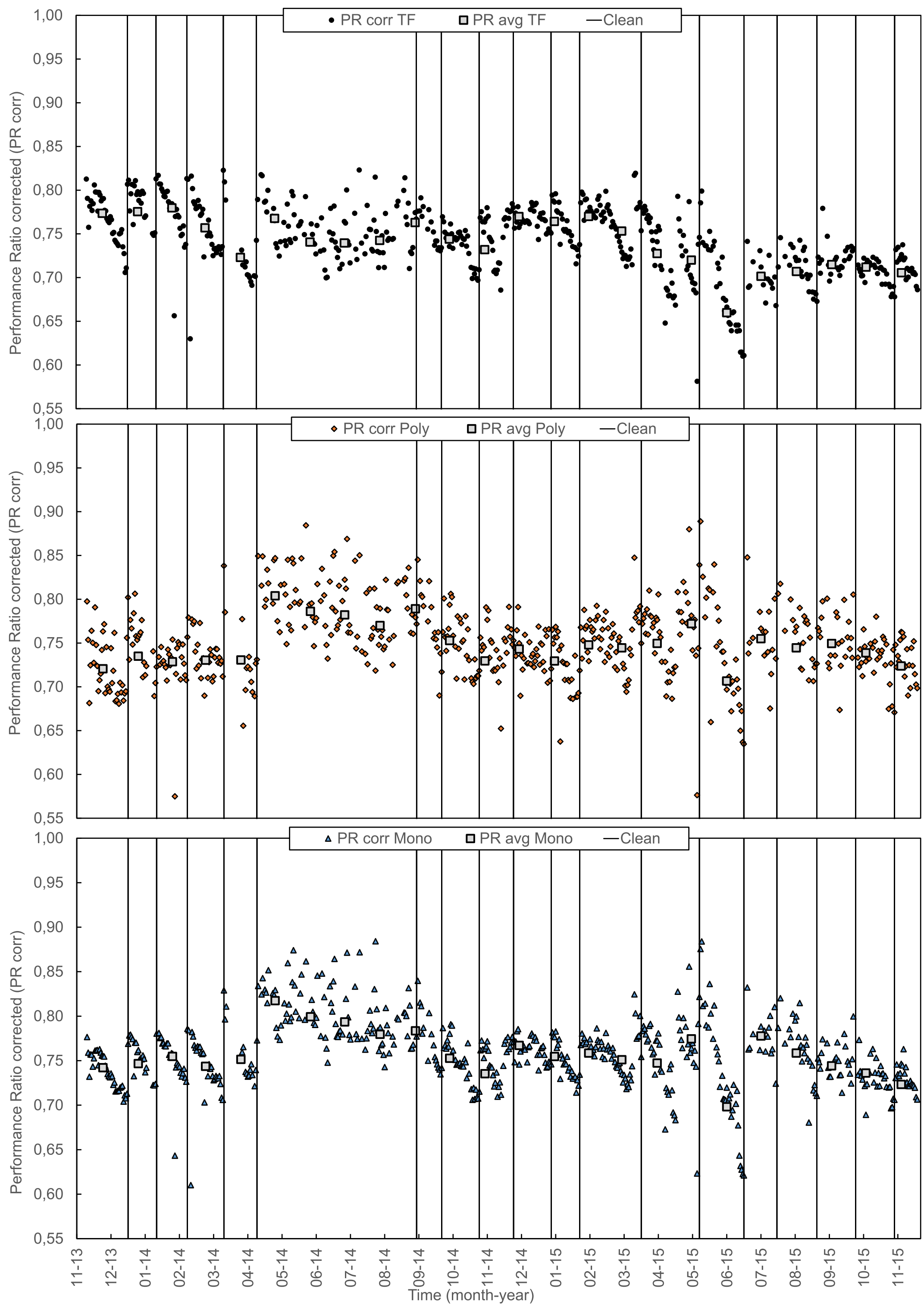


**Fig. 5.** Weather-corrected performance ratio in two years period December 2013 – November 2015, for TF, Poly and Mono PV arrays, respectively. Monthly cleaning is shown in full vertical lines. The time line is shown in the bottom *x*-axis in month-year format.

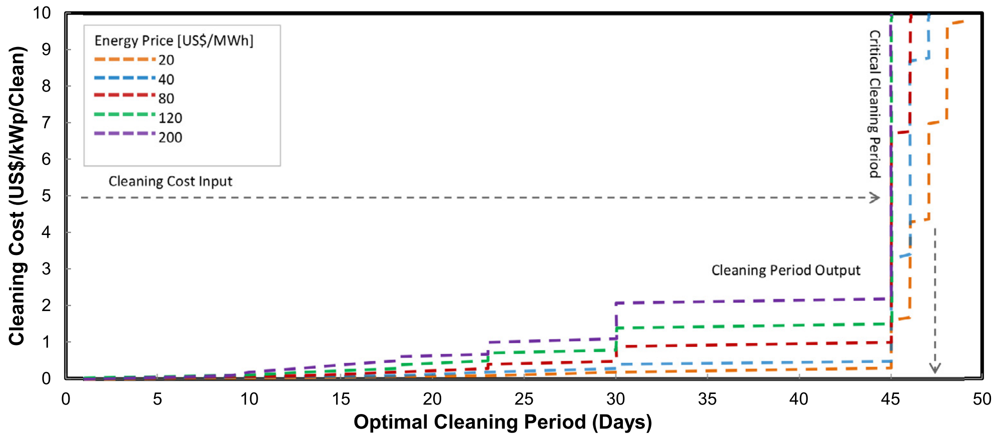


**Fig. 6.** Economical assessment for soiling, where critical cleaning day is defined.

attributed to a heavy light induced degradation phenomena, known as Staebler Wronski Effect (SWE) [37], from which thin film technology suffers. As well, for crystalline technologies, a degradation on panel output of 0.5%/year is normally considered [36] after the first year of operation. However, it is difficult to estimate the degradation of the whole system, not considering the panel.

### *5.4. Economic assessment*

The economic impact of soling has been studied, based on the prior PR analysis. The considered parameters for this study were the daily production of the polycrystalline array in one optimal period between 02.02.14 (immediately after cleaning) and 21.02.14 (immediately before cleaning). The daily PR and daily generation for the Mono array were, 78.1% and 9272 W h at the beginning (02.02.14), and 73.7% and 8543 W h at the end of the period (21.02.14), respectively. A daily linear seasonal decay was calculated as −0.24%. This decay was assumed to remain linear in the remaining months if cleaning was not performed. Thus, our analysis runs from a starting point of a cleaned system for a summer season.

Economic parameters, such as energy price (20–200 USD/MW h), cleaning costs (0–10 USD/kWp/Clean) and discount rate (10% annual) are also defined in our simulation. We defined a business as usual (BAU) case by creating a synthetic daily production profile during the summer season without cleaning, subject to the given PR decay, while the test case is a synthetic production profile subject to parameterized constant cleaning periods. The exercises cost of cleaning, relative to the BAU case, determines the optimal strategy period for cleaning, given a future energy price and cleaning cost per installed kWp.

Fig. 6 illustrates the optimal strategies of cleaning for different energy prices in USD/MW h. The zero cost cleaning case presents a trivial solution, which identifies a cleaning period of one day (cleaning every day). In the other case, the non-trivial solutions present increasing periods of optimal cleaning for incremental cleaning costs per installed kWp for a given energy selling price.

This trend finishes approximately at the 45th day cleaning period. For different cleaning costs and energy prices, the system presents a soft barrier of cleaning or CCP defined as the critical cleaning period (CCP).

CCP represents the threshold day, where independently of cleaning costs and energy price (except for the trivial null case), the optimal cleaning decision should not pass this value. This parameterized simulation was based on the real energy production of our test plant, its respective PR and production of an ideal summer day, and its respective PR decay (assuming a linear adjust). This methodology can be applied to any PV technology.

## 6. Conclusions

It is of paramount importance to understand the frequency of cleaning of photovoltaic solar systems. The cash inflow can vary depending on yearly degradation of the whole system and on monthly decay due to soiling. We show 2 years collected data of the in-plane irradiation present in Santiago, Chile, and the performance of solar arrays under real exposure as soiling. It has been found, that the whole system degrades down to 2.77% (thin film), 1.29% (polycrystalline), and 1.74% (monocrystalline), from the first to second year of operation. The performance ratio was highly dependent on ambient temperature so that a weather-correction has been applied, showing 75% performance for all technologies in the first year. Independent on cleaning cost and energy prices, a soft barrier at the 45th threshold day has been found, as a critical cleaning period (CCP) for our real case in Santiago. Furthermore, in order to understand in detail the detrimental effects of soiling, microscopical analysis and characterization of particles size will be performed in the future. Our results can be applied to real PV plants in Chile, taking into account the solar assessment progress of the recent years and the increasing knowledge of the soiling effect on energy generation decay.

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