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Optimum cleaning schedule of photovoltaic systems based on levelised cost of energy and case study in central Mexico

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Abstract

In this paper, the soiling impact on photovoltaic systems in Aguascalientes, in central Mexico, an area where 1.4GWp of new photovoltaic capacity is being installed, is characterised experimentally. A soiling rate of -0.16 %/day in the dry season for optimally tilted crystalline silicon modules, and a stabilization of the soiling losses at 11.2% after 70 days of exposure were observed. With this data, a first of its kind novel method for determining optimum cleaning schedules is proposed based on minimising the levelised cost of energy. The method has the advantages compared to other existing methods of considering the system investment cost in the determination of the optimum cleaning schedule. Also, it does not depend on economic revenue data, which is often subject to uncertainty. The results show that residential and commercial systems should be cleaned once per year in Aguascalientes. On the other hand, cleaning intervals from 12 to 31 days in the dry season were estimated for utility-scale systems, due to the dramatic decrease of cleaning costs per unit photovoltaic capacity. We also present a comparative analysis of the existing criteria for optimising cleaning schedules applied to the same case study. The different methods give similar cleaning intervals for utility-scale systems and, thus, the choice of a suitable method depends on the availability of information.

Keywords: cleaning schedule, crystalline silicon, levelised cost of energy, Mexico, photovoltaic, soiling.

Nomenclature

a	Fitting coefficient for modelling the soiling factor, day^{-1}
b	Fitting coefficient for modelling the soiling factor, dimensionless
C_0	Photovoltaic system cost per kWp, USD/kWp
C_{0_ec}	PV system cost financed through equity capital per kWp, USD/kWp
C_{0_loan}	PV system cost financed through a loan per kWp, USD/kWp
C_{clean}	Cost of each cleaning operation per kWp, USD/kWp
d	Nominal discount rate, per unit
d_{ec}	Annual payback in the form of dividends, per unit
F_{soil}	Soiling factor, dimensionless
G	Plane-of-array global irradiance, W/m^2
i_l	Annual loan interest, per unit
I_{sc}	Short-circuit current
K_d	Coefficient equal to $(1-r_d)/(1+d)$, dimensionless
K_p	Coefficient equal to $(1+r_{OM})/(1+d)$, dimensionless
L_0, L_1, L_2	Loss coefficients that characterise the inverter efficiency curve, dimensionless
L_{AC}	Coefficient of losses in the AC-side, per unit
LCC	Life-cycle cost per kWp, USD/kWp
$LCOE$	Levelised cost of energy, USD/kWh
L_{DC}	Coefficient of losses in the DC-side, per unit
N	Number of years of the life cycle, years
n_{clean}	Number of cleaning operations per year, dimensionless
N_d	Tax life for depreciation, years
N_l	Years for the loan to be repaid, years
p_{in}	Input power to the inverter normalized to the inverter nominal power, dimensionless
p_l	Fraction of the PV system cost financed through a loan, per unit
$PM10$	Paticulate matter, particles with diameter lower than 10 µm, µgr/m^3
$PM2.5$	Paticulate matter, particles with diameter lower than 2.5 µm, µgr/m^3
p_{sys}	Power generated by a 1 kWp photovoltaic system, kW/kWp
PV_{AOM}	Annual operation and maintenance cost per kWp, USD/kWp
$PW[DEP(N_d)]$	Present worth of the tax depreciation, USD/kWp
$PW[PV_{OM}(N)]$	Present worth of operation and maintenance cost per kWp, USD/kWp
q	Coefficient equal to $1/(1+d)$, dimensionless
r	Normalization ratio of a measured module, dimensionless
r_d	Annual degradation rate of photovoltaic module efficiency, per unit
r_{DCAC}	DC-to-AC inverter sizing ratio, dimensionless
r_{OM}	Annual escalation rate of the operation and maintenance cost, per unit
T	Income tax rate, per unit
t	Time, days
t_0	Fitting coefficient for modelling the soiling factor, days

T_{cell}	Cell temperature, °C
Y	Annual energy yield, kWh/kWp

Greek symbols

γ	Temperature coefficient of maximum power, °C^{-1}
Δt	Time step for the simulations, h
η_{inv}	Inverter efficiency, per unit

Abbreviations

AC	Alternating Current
CENACE	Centro Nacional de Control de Energía
CGSMN	Coordinación General del Servicio Meteorológico Nacional
CONAGUA	Comisión Nacional del Agua
DC	Direct Current
IEC	International Electrotechnical Commission
INECC	Instituto Nacional de Ecología y Cambio Climático
MBE	Mean Bias Error
PV	Photovoltaic
RMSE	Root Mean Square Error
WACC	Weighted Average Cost of Capital

1. Introduction

The natural deposition of dust, particles and, dirt on the photovoltaic (PV) modules, named soiling, can affect significantly the energy generation of PV systems. Soiling accumulates during the dry periods between cleaning events, and can be naturally removed by rain and other natural events, or artificially removed by cleaning the PV modules. Determining a good cleaning strategy is essential for improving the profitability of a PV system, where a careful balance between the cost of cleaning operations and the benefits obtained in the form of increasing energy yield (and increasing revenues) must be considered.

The scientific community is paying great attention to the mechanisms and impact of soiling in solar energy systems because of the influence in energy production and economics of solar plants worldwide (Costa et al., 2018, 2016). However, there are not many findings dealing with optimisation of cleaning schedules, a critical topic especially regarding utility-scale PV plants, where small drops in the energy yield cause impressive economic losses and large operation and maintenance teams are involved. Some authors have characterised the soiling impact at specific sites and have given recommendations for cleaning in a qualitative way.

In (Kalogirou et al., 2013), three PV technologies (mono-crystalline, poly-crystalline and amorphous silicon) were experimentally analysed in Cyprus considering the episodes of dust storms from North Africa. Authors recommended cleaning the systems every 2-3 weeks in the dry season. In (Fuentealba et al., 2015), the energy yield of two PV technologies (poly-crystalline and, amorphous/microcrystalline silicon) was monitored during 1.5 years at the Atacama Desert and, based on the experimental data, authors recommended cleaning schedules by differentiating between summer and winter seasons and, between both technologies. In (Jiang et al., 2016), authors developed a physical model that characterises the rate of particle deposition in desert regions. The cleaning operations were then recommended when the efficiency loss due to soiling reaches 5% compared to the clean efficiency. In (Fathi et al., 2017), authors evaluated the "soiling threshold" for two PV technologies (mono-crystalline silicon and, CdTe) in Algeria. This minimum soiling loss makes profitable a two-cleanings per year schedule, and corresponds to 7.3% for mono-crystalline and, 6.8% for CdTe. In (Conceição et al., 2019), a model intended for calculating the effective irradiance under soiling as a function of the PV module tilt angle at the Alentejo region, Portugal, was developed. By comparing the effective irradiance in soiled and clean scenarios, the period of the year in which it would be desirable to perform cleaning operations can be determined, but not the time interval for cleaning schedule. These contributions have as a common feature that the cleaning operations are recommended based on the criterion of the experts.

Other authors have implemented criteria that are more systematic. In (Tanesab et al., 2018), the cleaning schedule of grid-connected and stand-alone PV systems in Australia and Indonesia was determined by matching the annual revenue loss due to soiling to the annual cleaning cost. This criterion was also used in (Sulaiman et al., 2018) giving a 2.5 months interval between cleaning operations in Malaysia. A similar approach was applied in Santiago, Chile, by monitoring the performance ratio of mono-crystalline, poly-crystalline and, amorphous silicon during two years, and defining a critical interval of 45 days between cleaning operations for the three technologies (Urrejola et al., 2016). A different criterion, based on formulating an optimisation problem that maximizes the difference between annual revenues and annual cleaning costs, was used in (Besson et al., 2017), also applied to the soiling characterisation of three PV technologies during 2.5 years in Santiago, Chile. This

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methodology was modified in (Luque et al., 2018) for analysing bifacial modules and differentiating the cleaning schedules for the front surface and the back surface of the modules. Another approach in Saudi Arabia considered the problem of minimising the function $(V_L+C_C)/V_S$, where V_L is the annual revenue loss due to soiling, C_C is the annual cleaning cost and, V_S is the annual revenue (Jones et al., 2016). All of these criteria use an objective function in a particular year of operation. To our knowledge, there is only one contribution that has proposed an objective function extended over the whole life cycle of the PV system, i.e. maximising the Net Present Value (You et al., 2018). In this study, seven cities worldwide were analysed based on one year of experimental data.

In this paper, we propose a novel method for optimising the cleaning schedule based on minimising the levelised cost of energy (*LCOE*). Similarly to the approach in (You et al., 2018), and differentiating from the other reviewed approaches, we consider an objective function extended over the whole life cycle of the PV system, which should give more reliable results. By using this method, the influence of the system investment cost, which can vary significantly as a function of the system size, on the optimum cleaning schedule is analysed for the first time. One of the advantages of this method compared to the rest of reviewed methods is that it does not require economic revenue data, which is often subject to uncertainty. In addition, in the last part of the study, we present a comparative analysis of the different existing criteria for optimising cleaning schedules applied to the same case study. This is the first time this kind of analysis is done and it sheds light on the choice of the existing alternatives.

The method is applied to the semi-desert climatic and soiling conditions of Aguascalientes, central Mexico. Aguascalientes State, in spite of its small size (5616 km^2), is highlighting as one of the most important regions in Mexico for PV system facilities. This is because it combines a high solar resource (2125 kWh/m^2/year global horizontal irradiation according to the data used in this study, see section 2.1) with temperatures warmer than the Northern deserts of Mexico, and lower soiling impact. The PV projects that were awarded in the last three long-term auctions derived from the energetic reform in Mexico corresponding to Aguascalientes State are presented in Table 1 (Centro nacional de Control de Energía (CENACE), 2018). As can be seen, a total of 1429 MWp PV power has been or is going to be installed imminently in this State thanks to its high solar potential. The results presented in this paper are supported by the experimental measurements of soiling factors registered in Aguascalientes. To the best of our knowledge, there is only one paper analysing the soiling impact in Mexico, and it corresponds to the Northern Sonora's desert (Cabanillas and Munguía, 2011). In that paper, the soiling losses of three PV technologies (mono-, poly- and, amorphous silicon) were characterised, but no conclusions on the optimum cleaning schedule were extracted. The present paper will provide a robust tool to characterize the soiling loss at a site and to identify the most convenient cleaning schedule, in order to maximize the energy yield and the profitability of PV systems.

Table 1. PV projects awarded in the last three long-term auctions in Mexico corresponding to Aguascalientes State (Centro nacional de Control de Energía (CENACE), 2018).

Name of the project	**Company**	**Country**	**Peak power (MWp)**
Solem I - Solem II	Alten	Spain - Canada - Mexico	350
Pachamama	Neoen	France	300
Tepezalá II Solar	Consorcio SMX	Mexico - USA	300
Trompezón	Engie	France	126
Las Viborillas	Jinkosolar Investment	China	100
Horus AG	Canadian Solar	Canada - Mexico	95
Aguascalientes Potencia 1	Recurrent Energy Mexico Development	Canada - Mexico	63
Aguascalientes Sur 1	OPDE	Spain	59
San Bartolo	Infraestructura Energética del Norte	Mexico	34.9
Parque Solar Bicentenario	Autoabastecimiento Renovable	Mexico	0.79

2. Materials and methods

2.1. Atmospheric data

Typical data of global horizontal irradiance, ambient temperature, rainfall and, particulate matter of Aguascalientes city (21.9ºN, -102.3ºE) have been collected for carrying out this study. The global horizontal irradiance and ambient temperature data were supplied by the Coordinación General del Servicio Meteorológico Nacional (CGSMN) of the Comisión Nacional del Agua (CONAGUA). It is a dataset that covers 10 years of measurements (from

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December 2005 to April 2015) at 10-minute intervals taken at an atmospheric station near the center of the city. This dataset has been processed to get the typical year of irradiance and temperature. For each month (January, February, etc.), we have searched the month in the dataset that better matches the average monthly global horizontal irradiation. For instance, considering January, January 2009 had 4.62 kWh/m^2/day, which is close to the average 4.54 kWh/m2/day obtained for all the January months in the dataset. These real months from different years are linked to get the typical meteorological year of global irradiance and temperature (Rodrigo et al., 2016). In addition, the histograms of irradiance and temperature have been analysed to guarantee that the generated typical year has a similar distribution than the 10 years' dataset. As an example of these histograms, the annual distribution of irradiance and temperature is shown in Fig. 1, where an acceptable matching between the typical year and the 10 years' dataset can be observed. As a conclusion, we assessed that the generated typical year represents adequately the average climate of the location.

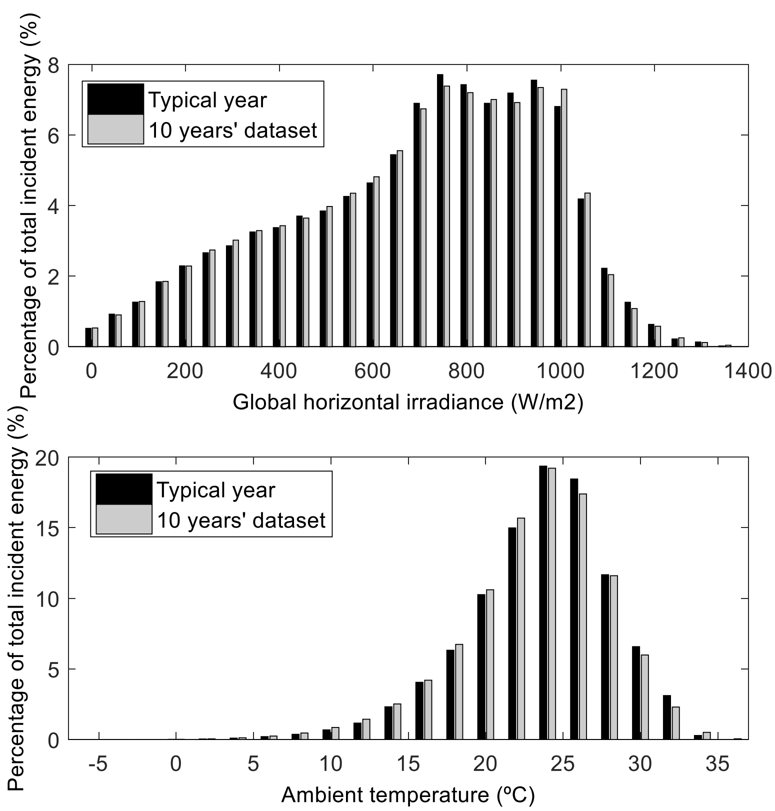

Fig. 1. Comparison between the annual histograms of global horizontal irradiance (top) and ambient temperature (bottom) corresponding to the generated typical year and the 10 years' dataset in Aguascalientes.

In this study, south-oriented 20º tilted PV systems are considered, which is the typical configuration of mounting structures in the region and represents optimum tilt and orientation to maximise annual energy harvesting for fixed structure systems in Aguascalientes. The three components of solar radiation (direct, diffuse and albedo) on the plane of the PV generator have been modelled. The Iqbal's correlation to compute the diffuse fraction (Iqbal, 1983), the Hay's anisotropic sky diffuse model (Hay, 1979) and, an isotropic model with constant albedo coefficient of 20% are used for this purpose, according to previously published contributions (Rodrigo, 2017; Rodrigo et al., 2016; Sánchez-Carbajal and Rodrigo, 2019). In addition, the cell temperature of the PV modules is calculated from ambient temperature and plane-of-array global irradiance based on the Nominal Operating Cell Temperature method (International Electrotechnical Commission (IEC), 2011).

The monthly average rainfall in the 1981-2010 period has been retrieved from (Servicio Meteorológico Nacional, 2019) and is shown in Fig. 2. It can be seen that the typical meteorological year in Aguascalientes can be divided into two seasons: the dry season, covering a period of eight months from October to May and, the wet season, covering a period of four months from June to September. In the dry season, the rainfall events are very scarce in this region, with a mean monthly rainfall of 12.7 mm. In the wet season, there are frequent storms, typically every day, and the mean monthly rainfall is 101.2 mm. In the wet period, the 80% of the accumulated rainfall occurs. The monthly average particulate matter (*PM2.5* and *PM10*) calculated as the average of the daily measurements is also represented in Fig. 2 for the year 2018, taken from (Instituto Nacional de Ecología y Cambio Climático (INECC), 2019). Regarding *PM2.5*, the behaviour in 2018 was quite stable over the whole year, with monthly average values between 10 and 29 μgr/m^3, and no important seasonal variations. Regarding *PM10*, it can be differentiated two different levels of particulate matter in 2018: one that covers approximately the dry season (values between 39 and 56 μgr/m^3, except for the anomalous October, with 26 μgr/m^3) and, another that covers approximately the wet season (values between 22 and 28 μgr/m^3, except for the anomalous July, with 41 μgr/m³). By analysing these values of 2018, it can be said that the *PM2.5* behaviour seems to be stable over the year, while the *PM10* behaviour could be divided into the dry season (with higher values) and the wet season (with lower values). It can be highlighted that neither *PM2.5* nor *PM10* show appreciable seasonality effects in the dry season, which is the focus of the soiling analysis in this paper.

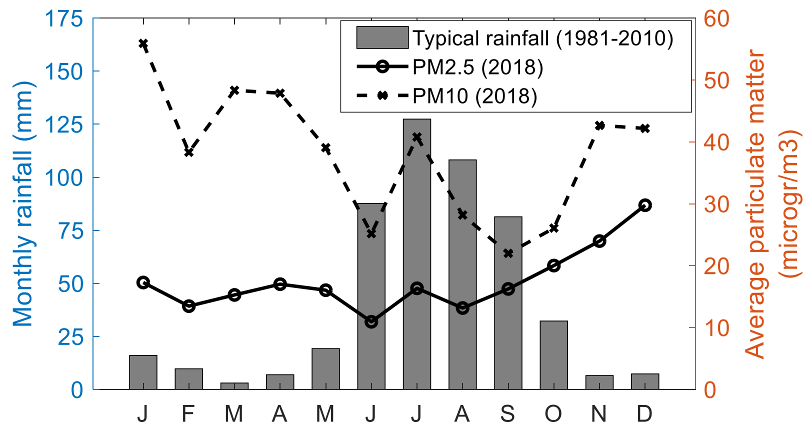

Fig. 2. Monthly average rainfall (1981-2010) and average particulate matter (2018) in Aguascalientes (Instituto Nacional de Ecología y Cambio Climático (INECC), 2019; Servicio Meteorológico Nacional, 2019).

2.2. Experimental set-up and soiling characterisation

An experimental set-up was installed at the research facilities of the Engineering Faculty of Panamericana University in Aguascalientes. The set-up consisted in three 60-cells poly-crystalline PV modules, model Risen RSM60-6-260P, mounted on a south-oriented 20º tilted structure (Fig. 3). The characteristics of the modules at Standard Test Conditions are shown in Table 2. The aim of the set-up is to measure the soiling factor (F_{soil}) of two modules, which are naturally soiled, taking as reference the third module, which is cleaned each day of measurement. Before beginning the soiling characterisation, it was necessary to check that the three modules have very similar electrical response. For this purpose, the three modules were perfectly cleaned, and exposed to natural sunlight during a clear day. The simultaneous measurement of the three short-circuit currents at 15-minute intervals from 10:00 a.m. to 4:00 p.m. are shown in Fig. 4. The numerical values of Mean Bias Error (MBE) and Root Mean Square Error (RMSE) of the modules A and B (those that will be exposed to natural soiling) with reference to the third module, which will be cleaned during the experimental campaign, are shown in Table 3. The obtained errors are small enough for soiling measurements. The normalization ratio of each module (r) is also shown in the table, understood as the average ratio of short-circuit current of the module to the short-circuit current of the reference module.

Fig. 3. Photo of the experimental set-up at the facilities of Panamericana University, Aguascalientes campus.

Table 2. Characteristics of the analysed PV modules at Standard Test Conditions.

Parameter	**Value**
Maximum power	260 Wp
Power tolerance	0-4.99 W
Maximum power point voltage	30.6 V
Maximum power point current	8.50 A
Open-circuit voltage	37.8 V
Short-circuit current	9.04 A
Module efficiency	15.9 %
Nominal operating cell temperature	45±2 ºC
Temperature coefficient of maximum power	-0.39 %/ºC

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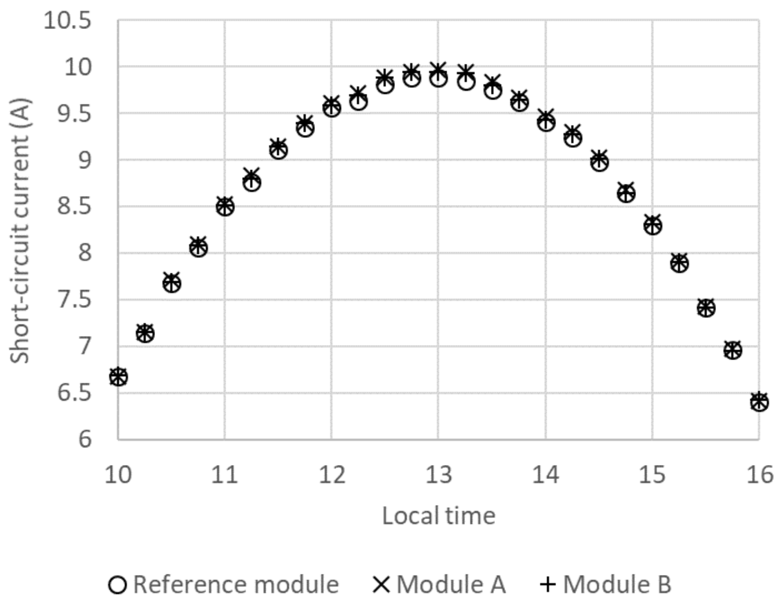

Fig. 4. Measurements of the short-circuit currents of the three analysed PV modules after cleaning over a clear day from 10:00 a.m. to 4:00 p.m. The reference module is the one that will be kept clean over the soiling characterisation.

Table 3. Mean Bias Error (MBE) and Root Mean Square Error (RMSE), calculated from short-circuit current measurements of the modules A and B compared to the reference module. The normalization ratio of each module is also shown.

PV module	**MBE (%)**	**RMSE (%)**	**Normalization ratio (*r*)**
A	0.49	0.56	1.004923
B	0.32	0.40	1.003153

An experimental campaign of 110 days was carried out in the dry season of 2019. During this campaign, modules A and B were not cleaned and, thus, were exposed to natural soiling. The reference module was cleaned periodically in intervals from 5 to 10 days. Each day the reference module was cleaned, a set of six measurements of the short-circuit currents was performed at 15-minute intervals around noon. As the short-circuit currents were measured around noon, angle-of-incidence, spectral and, low irradiance effects, which could distort the measurements, were avoided. Measurements under cloudy conditions (global horizontal irradiance < 500 W/m^2) were also removed to avoid low irradiance uncertainties. The soiling factor of module "*i*" ($F_{soil,i}$) for each measurement is defined in this study as the ratio of the short-circuit current of the "*i*" soiled module ($I_{sc,i,soil}$) to the short-circuit current of the reference clean module ($I_{sc,ref,clean}$), divided by the normalization ratio of the "i" soiled module (r_i):

$$F_{soil,i} = \frac{I_{sc,i,soil} / I_{sc,ref,clean}}{r_i} \quad (1)$$

The soiling factor is equivalent to the soiling ratio used by other authors (International Electrotechnical Commission, 2017). The soiling losses can be extracted as 1- $F_{soil,i}$, and are here expressed as percent. The six measurements were averaged each cleaning day to get the F_{soil} for that day. Thus, F_{soil} of modules A and B with reference to the clean module were obtained every 5-10 days during the experimental campaign. The behaviour of F_{soil} of modules A and B over this experiment is shown in Fig. 5. (Gostein et al., 2013) showed that the F_{soil} measured from short-circuit currents is a very good approach to correct the maximum power of soiled PV modules, in conditions of uniform soiling and loss level below 11%. For heavier soiling, nonuniformity of illumination and soil accumulating near the module corners can cause current matching in strings and hot temperatures in some cells, which would invalidate the approach based on the short-circuit current measurement (Gostein et al., 2014). In our experiment, maximum soiling losses of about 11%, corresponding to a soiling factor of 0.89, were registered, and visual inspection of the soiled modules for checking the uniform deposition was done, so that the approach based on short-circuit current measurements can be considered adequate.

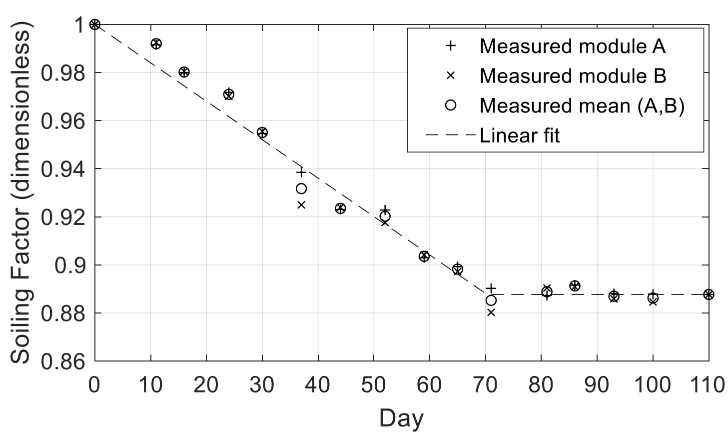

Fig. 5. Measurement of the soiling factor of modules A and B during the experimental campaign, and linear fit of the data for modelling purposes.

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The experimental data in Fig. 5 allowed the natural soiling of optimally tilted crystalline PV modules in the dry season of Aguascalientes to be characterised. As can be seen, the F_{soil} follows an approximately linear descendent behaviour until a threshold value, in which soiling losses stabilize. This behaviour is similar to that observed in other published studies, for instance in (Kalogirou et al., 2013), where the soiling losses stabilized after nine weeks of exposure in the summer season of Cyprus. Taking into account the experimental data, the F_{soil} after a cleaning operation in the dry season can be modelled as a function of time (t in days) as:

$$F_{soil}(t) = \begin{cases} 1 - a \cdot t, & t \le t_0 \\ b, & t > t_0 \end{cases} \tag{2}$$

With fitted values of a= 0.001598 (R^2=0.977), b= 0.8877 and, t_0=70.3 (Fig. 5). This means that the natural soiling in the dry season follows a soiling rate (here labelled as a) of -0.16 %/day until the 70th day after cleaning, in which soiling losses stabilize at 11.2%.

In this work, the soiling factor profile is built according to the Fixed Rate Precipitation model (Kimber et al., 2007). This is the first, and still one of the most common, soiling extraction model and is based on the assumption that the soiling factor profile at a site can be determined by alternating soiling deposition periods (that follow Eq. (2)) and cleaning events, that raise the soiling factor to 1. In this work, only rainfall events are found to have a cleaning effect on the photovoltaic modules. Therefore, the soiling profile in this work is built based on the previously shown wet and dry periods. No soiling accumulation occurs during the wet season, because of the daily frequency of rainfalls. For this reason, the soiling factor is assumed to be 1 during the wet months. On the other hand, there were no rainfall events during the 110 day experimental campaign, which is the typical climatic behaviour in the dry season of Aguascalientes. It can be also highlighted that the soiling behaviour was very similar for the modules A and B, as can be seen in Fig. 5, which gives reliability to the soiling characterisation. In this study, the F_{soil} is assumed to propagate according to Eq. (2) after a cleaning operation in the dry season. This means that we assume the soiling rate to be constant during the dry season, in accordance also with the original model proposed by (Kimber et al., 2007). The seasonal variability of soiling rates is currently object of intense research (Micheli et al., 2019, 2017). However, in the specific climate of Aguascalientes, the particulate matter levels in the dry season are quite stable (Fig. 2), so that appreciable changes in the soiling deposition rates are not expected (Coello and Boyle, 2019).

2.3. Energy yield model

The power generated by a PV system of 1 kWp capacity (in kW/kWp) can be expressed as:

$$p_{sys} = \frac{G}{1000\,W/m^2} \cdot F_{soil} \cdot \left[1 + \gamma \cdot \left(T_{cell} - 25^{\circ}C\right)\right] \cdot \left(1 - L_{DC}\right) \cdot \eta_{inv} \cdot \left(1 - L_{AC}\right) \quad (3)$$

Where G is the plane-of-array global irradiance (W/m^2), F_{soil} is the soiling factor for the day considered (per unit), γ is the temperature coefficient of maximum power of the PV modules (ºC^{-1}), T_{cell} is the cell temperature (ºC), L_{DC} is the coefficient representing losses in the DC-side in per unit (angular, spectral, low irradiance, shading, electrical mismatch and, DC wires heating), η_{inv} is the inverter efficiency (per unit) and, L_{AC} is the coefficient representing losses in the AC-side in per unit (AC wires heating and, power transformer if present). In this study, soiling, temperature and, inverter losses are calculated in detail, while the rest of DC and AC losses are represented by typical average annual coefficients, i.e. L_{DC} of 7.5% and, L_{AC} of 1.5% (Rus-Casas et al., 2014).

The inverter efficiency is calculated from the DC input power to the inverter normalized to the inverter nominal power (p_{in}), which can be expressed as:

$$p_{in} = r_{DCAC} \cdot \frac{G}{1000\,W/m^2} \cdot F_{soil} \cdot \left[1 + \gamma \cdot \left(T_{cell} - 25^{\circ}C\right)\right] \cdot \left(1 - L_{DC}\right) \quad (4)$$

Where r_{DCAC} is the DC-to-AC inverter-sizing ratio, or ratio of PV array peak power to inverter nominal power. r_{DCAC} is set in this study to 1.2 according to optimal values found for crystalline silicon modules in Aguascalientes (Rodrigo et al., 2016). The inverter efficiency can then be calculated by:

$$\eta_{inv} = \min\left\{1 - \left(L_0 + L_1 p_{in} + L_2 p_{in}^2\right)/p_{in}, 1/p_{in}\right\} \quad (5)$$

Where L_0=0.0048, L_1=0.0159 and, L_2=0.0144 are the inverter loss coefficients representing typical medium efficiency inverters taken from (Pérez-Higueras et al., 2018). The first term in Eq. (5) corresponds to normal operating conditions, while the second term corresponds to the conditions in which the inverter limits the output power to its nominal power in periods of high irradiance.

F_{soil} is assumed to propagate according to Eq. (2) after each cleaning operation in the dry season, while it is set to one in the wet season, as no soiling deposits because of the daily rain events. Therefore, the pessimistic approach that there are not rainfall events in the dry season, and the optimistic approach that the frequent rainfall events in the wet season keep the modules perfectly clean, are used in this study to estimate the energy yield. Also, when a cleaning operation is performed in the dry season, F_{soil} is reinitialized to one and a positive offset is transmitted until the following rainfall. These assumptions allow the energy yield calculation to be simplified and are expected to be valid for the climate of Aguascalientes in a long-term life cycle analysis.

The annual energy yield in kWh/kWp/year (Y) is obtained as:

$$Y = \sum\nolimits_{year} p_{sys,i} \cdot \Delta t \tag{6}$$

Where Δt is the time step for the simulation (1/6 hr in this study).

2.4. Levelised cost of energy model

The methodology for calculating the $LCOE$ is similar to that proposed in (Talavera et al., 2019). The general formulation of the $LCOE$ in this study is:

$$LCOE = \frac{LCC}{Y \cdot \dfrac{K_d \cdot \left(1 - K_d^N\right)}{1 - K_d}} \tag{7}$$

$$K_d = \left(1 - r_d\right) / \left(1 + d\right) \tag{8}$$

Where LCC is the life-cycle cost per kWp-installed capacity, N is the number of years of the life cycle, r_d is the annual degradation rate of PV module efficiency, and d is the nominal discount rate. The LCC can be broken down as:

$$LCC = C_0 + PW\left[PV_{OM}\left(N\right)\right] - PW\left[DEP\left(N_d\right)\right] \cdot T \tag{9}$$

Where C_0 is the system cost per kWp, $PW[PV_{OM}(N)]$ is the present worth of operation and maintenance cost per kWp, $PW[DEP(N_d)]$ is the present worth of the tax depreciation, and T is the income tax rate.

Concerning the operation and maintenance cost of the life cycle of the system, $PW[PV_{OM}(N)]$ can be written as:

$$PW\left[PV_{OM}\left(N\right)\right]=PV_{AOM}\cdot\left(1-T\right)\cdot\frac{K_p\cdot\left(1-K_p^N\right)}{1-K_p} \tag{10}$$

$$K_p=\left(1+r_{OM}\right)/\left(1+d\right) \tag{11}$$

Where PV_{AOM} is the annual operation and maintenance cost per kWp, and r_{OM} is the annual escalation rate of the operation and maintenance cost. r_{OM} takes the value of the average inflation rate in this study. PV_{AOM} is the product of the number of cleaning operations per year (n_{clean}) by the cost of each cleaning operation per kWp-installed capacity (C_{clean}):

$$PV_{AOM}=n_{clean}\cdot C_{clean} \tag{12}$$

The tax depreciation is calculated as lineal over the time period:

$$PW\left[DEP\left(N_d\right)\right]=\frac{C_0}{N_d}\cdot\frac{q\cdot\left(1-q^{Nd}\right)}{1-q} \tag{13}$$

$$q=1/\left(1+d\right) \tag{14}$$

Where N_d is the tax life for depreciation in years.

The share of debt financing and equity financing can be included in the analysis explicitly through the weighted average cost of capital (WACC) over the discounting factor (nominal discount rate). C_0 is assumed to be financed through debt -a loan- (C_{0_loan}) and equity capital (C_{0_ec}) so that can be written as:

$$C_0=C_{0\_loan}+C_{0\_ec} \tag{15}$$

The C_{0_loan} and C_{0_ec} can then be evaluated as:

$$C_{0\_loan} = \left(p_l \cdot C_0\right) \cdot \frac{i_l \cdot (1-T)}{1-\left[1+i_l \cdot (1-T)\right]^{-N_l}} \cdot \frac{q \cdot \left(1-q^{N_l}\right)}{1-q} \tag{16}$$

$$C_{0\_ec} = d_{ec} \cdot \left[\left(1-p_l\right) \cdot C_0\right] \cdot \frac{q \cdot \left(1-q^{N}\right)}{1-q} + \left[\left(1-p_l\right) \cdot C_0\right] \cdot q^N \tag{17}$$

Where p_l is the fraction of system cost financed through a loan, i_l is the annual loan interest, N_l are the years for the loan to be repaid, and d_{ec} is the annual payback in the form of dividends.

It is worth mentioning that the left-hand side of Eq. (15) only equals its right-hand side if the selected value of d is equal to the WACC of the investment. WACC is the cost that the owner or investor of the project must pay for the use of capital sources in order to finance the investment. A widespread practice in organizations is to use a nominal discount rate (d) equal to the organization's WACC (Short et al., 1995). In this paper, d is assumed to be equal to WACC in order to calculate the *LCOE*.

The values of the *LCOE* parameters used in this study are shown in Table 4. The references that justify the choice of these parameters are also indicated in the table.

Table 4. Parameters used in the calculation of the *LCOE*.

Parameter	Value
C_0	1060-2700 USD/kWp[a]
C_{clean}	Residential: 7-11 USD/kWp/cleaning[b]
	Commercial: 4-8 USD/kWp/cleaning[b]
	Utility-scale: 0.03-0.21 USD/kWp/cleaning[c]
r_d	0.5%[d]
N	30 years[e]
N_l	20 years[e]
N_d	20 years[e]
i_l	5.3%[f]
d_{ec}	15.8%[f]
r_{OM}	4.2%[f]
d	10.9%[f]
p_l	50.0%[f]

[a] (Fu et al., 2018)
[b] Costs offered by PV suppliers in Aguascalientes region
[c] (Jones et al., 2016)
[d] (Branker et al., 2011; Jordan and Kurtz, 2013)
[e] (Talavera et al., 2019)
[f] (Talavera et al., 2016)

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2.5. Optimisation method

A graphical optimisation method is used for every simulated scenario. It is based on plotting the *LCOE* versus the number of days between cleaning operations. The minimum of the *LCOE* function corresponds to the optimum cleaning schedule in the dry season. As an example of this graphical procedure, the *LCOE* optimisation for a 1060 USD/kWp system cost and for costs of cleaning of 0.05 and 0.15 USD/kWp is shown in Fig. 6. The circles indicate the optimal points. Cleaning intervals of 14 and 25 days are obtained respectively. It can be highlighted that the lines are quite flat near the optimal points: this suggests that multiple scenarios can be applied, with limited variation to the results.

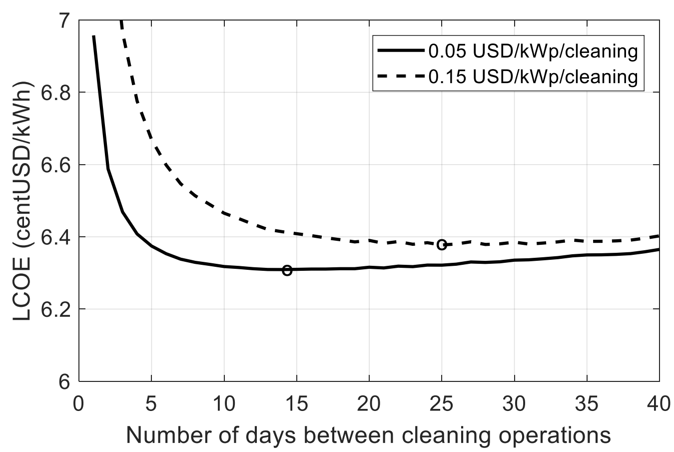

Fig. 6. Example of the graphical method to optimise cleaning schedules by minimising the *LCOE* for 1060 USD/kWp system cost. The minimum of the *LCOE* function is indicated with a circle.

3. Results

With the help of the energy yield model, the relation of the number of days between cleaning operations and the percentage of annual soiling losses can be characterised for Aguascalientes and is presented in Fig. 7. This graph can be useful to select a cleaning schedule that allows a specific percentage of soiling losses to be obtained. For instance, a 3% annual soiling level, which is recommended by some PV designers, can be obtained by cleaning the PV generator every 2 months in the dry season. However, these simple rules do not consider the balance between cleaning costs and benefits, and a more in deep analysis can be done with the proposed optimisation method.

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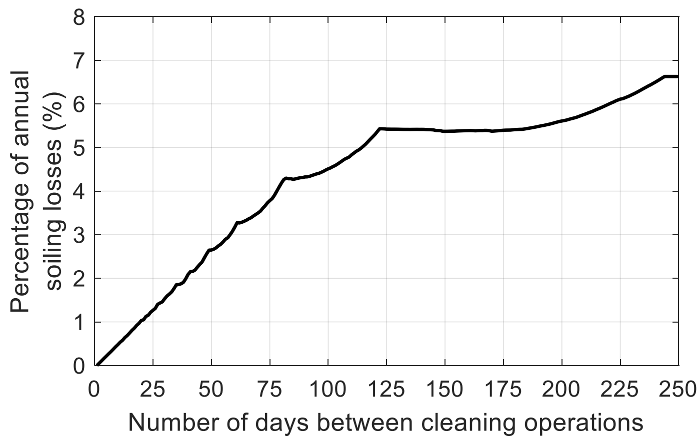

Fig. 7. Relation between the number of days between cleaning operations and the percentage of annual soiling losses obtained with the energy yield model.

Optimisation results are shown in Fig. 8 for a range of cleaning costs between 0.2 and 4.0 USD/kWp/cleaning and, various system investment costs from 1000 to 2700 USD/kWp. As can be seen, not only the cleaning cost determines the optimum strategy, but the system investment cost, closely related to the system size, influences as well. The influence of the system investment cost was not analysed in the existing literature. According to (Fu et al., 2018), the typical system cost nowadays in the U.S. is 1060 (utility-scale system >2MWp), 1830 (commercial system between 10kWp and 2MWp) and, 2700 (residential system between 3 and 10 kWp). In Fig. 8, it can be seen that the higher the system cost, the higher the optimum number of cleaning operations per year for the same cleaning cost. This is because when the system cost increases, the weight of the operation and maintenance cost in the life cycle cost decreases. The figure also shows the threshold values of cleaning costs required for a cleaning strategy to be cost-effective. For a 1000 USD/kWp system, cleaning costs must be lower than 1.4 USD/kWp for a cleaning strategy to be useful. As the system cost increases, this threshold value also increases (2.0 USD/kWp for a 1500 USD/kWp system; 2.6 USD/kWp for a 2000 USD/kWp system; and, 3.6 USD/kWp for a 2700 USD/kWp system).

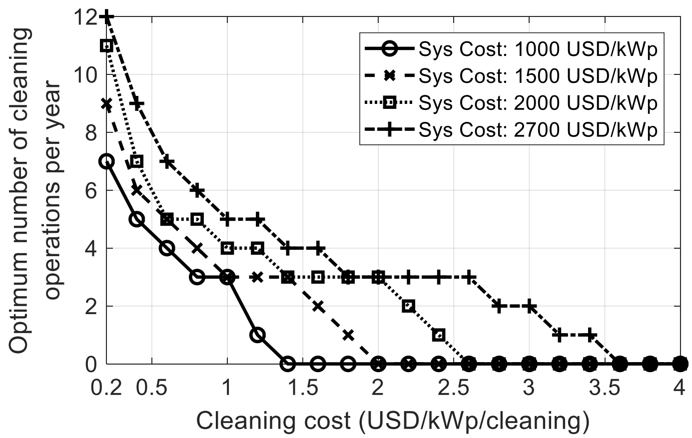

Fig. 8. Optimisation of the number of cleaning operations per year as a function of the cleaning cost and system cost for minimum *LCOE*.

The optimum percentage of annual soiling losses also depends on both the cleaning cost and the system cost, as can be seen in Fig. 9. For instance, for a cleaning cost of 1.0 USD/kWp, the cleaning of a 1000 USD/kWp system (utility-scale) should be scheduled to assess 3.3% annual soiling losses. However, for a 1800 USD/kWp system (commercial), the recommendation would be to operate under 2.6% annual soiling losses and, for a 2700 USD/kWp system (residential), the recommendation would be 2.2% annual soiling losses. These recommendations, based on minimising the *LCOE*, highlight again the influence of the system investment cost on the optimum cleaning schedule.

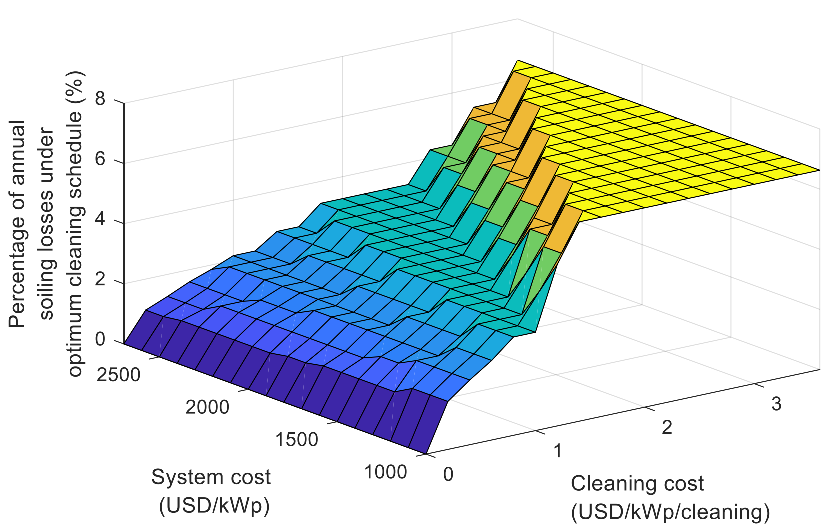

Fig. 9. Percentage of annual soiling losses under optimum cleaning schedule as a function of cleaning cost and system cost.

The economic benefits of implementing an optimum cleaning schedule in terms of *LCOE* reduction with reference to a no cleaning strategy are investigated in Fig. 10. It can be seen that, in the ideal case in which cleaning does not represent a cost, the maximum *LCOE* reduction is 6.6%. This percentage decreases as the cleaning cost increases. The graph exhibits that the decrease in the percentage is faster for a utility-scale system than for a residential system. Therefore, utility-scale systems require lower cleaning costs for the economic benefits of cleaning to be appreciable. This verifies in real PV systems, where the cleaning costs per unit PV capacity dramatically decrease as the system size increases.

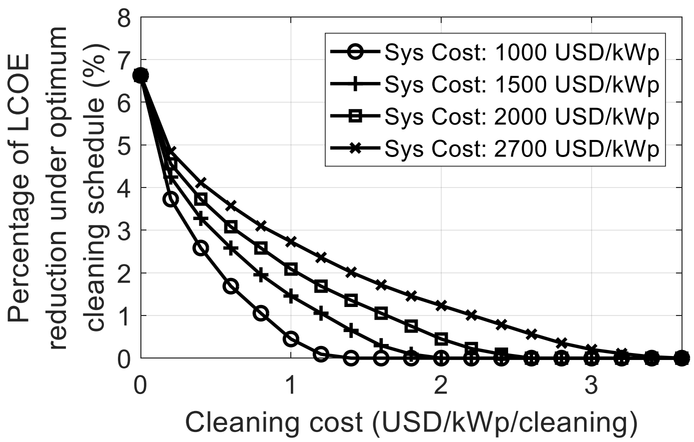

Fig. 10. Percentage of *LCOE* reduction with reference to a no cleaning strategy as a function of cleaning cost and system cost.

The numerical values of the optimal cleaning strategies for typical residential, commercial and, utility-scale PV systems in Aguascalientes are shown in Table 5. Representative system costs for each system size have been taken from (Fu et al., 2018) and are indicated in the table. The cleaning costs have been set according to typical ranges offered by PV suppliers in Aguascalientes for residential and commercial systems and, according to the range proposed by (Jones et al., 2016) for utility-scale systems. As can be seen, cleaning costs can vary in a wide range depending on the cleaning method, difficulties to access the PV generator, security issues and, system size. Utility-scale systems open the possibility of using machine-assisted cleaning, which decreases considerably the cleaning cost per kWp. In Table

5, it can be seen that commercial and residential PV systems with cleaning costs from 4 to 11 USD/kWp do not need to be cleaned over the year for minimising the *LCOE*. The cost of cleaning is too high for these systems and it exceeds the threshold values analysed in Fig. 8. Such a system that operates without cleaning maintenance would generate 1674 kWh/kWp/year with an annual soiling loss level of 6.6%. Of course, these numerical results can be questioned in the real world. Most PV systems should be cleaned at least once per year in order to remove the heavy soiling that cannot be removed by the rain and that could cause mismatch or overheating problems in the PV generator or lead to cementation and permanent contamination of the surface (Toth et al., 2018). Therefore, beyond the numerical values obtained from the optimisation method, the recommendation for commercial and residential PV systems would be to clean once per year, unless the owner is not interested in cleaning. The panorama is quite different for utility-scale systems. The low cleaning costs between 0.03 and 0.21 USD/kWp allow the implementation of an optimum cleaning schedule. For the case of 0.21 USD/kWp cleaning cost, an optimum cleaning schedule each 31 days in the dry season would lower the annual soiling losses to 1.6% with a *LCOE* reduction of 3.7%. For the case of 0.03 USD/kWp cleaning cost, cleaning each 12 days in the dry season would be cost-effective, lowering the annual soiling losses to 0.6% with a *LCOE* reduction of 5.5%. Therefore, for the considered cleaning cost ranges, utility-scale systems should be cleaned between 12 and 31 days in the dry season in Aguascalientes. The use of an optimisation method such as the one proposed here results essential for the operation and maintenance scheduling in these plants.

Table 5. Numerical values of the optimisation of the cleaning schedule for residential, commercial and, utility-scale PV systems in Aguascalientes.

System size	Residential (3-10 kWp)	Commercial (10 kWp-2 MWp)	Utility-scale (>2 MWp)	
System cost (USD/kWp)	2700	1830	1060	
Cleaning cost (USD/kWp/cleaning)	7-11	4-8	0.21	0.03
Days between cleaning operations	-	-	31	12
Number of cleaning operations per year	0	0	7	20
Annual Energy Yield (kWh/kWp)	1674	1674	1764	1782

Percentage of annual soiling losses (%)	6.6	6.6	1.6	0.6
LCOE (centUSD/kWh)	16.9	11.5	6.4	6.3
Percentage of LCOE reduction (%)	0.0	0.0	3.7	5.5

4. Comparative analysis

The different criteria proposed in the literature for optimising cleaning schedules in PV systems were reviewed in section 1. These criteria have been implemented under the climatic and soiling conditions of Aguascalientes in order to perform a comparative analysis for utility-scale systems. Results of this analysis are shown in Table 6. As can be seen, for a low cleaning cost (0.03 USD/kWp) there are very small differences in the optimum cleaning schedule, with days between cleaning operations in the range from 10 to 12 days. For a higher level of cleaning costs (0.21 USD/kWp), the differences are somewhat greater, ranging from 25 to 31 days between cleaning operations. It can be highlighted that the available methods require different information to be implemented. Methods 1, 2 and, 3 require economic revenue data, which is often subject to uncertainty, but have the advantage that are applied only to a specific year of operation, avoiding some information needed to perform a life cycle analysis. Method 4 is the more complex method, requiring economic revenue data, system cost data and, the parameters for the life cycle analysis. Our proposed method does not require economic revenue data, but require system cost data and the parameters for the life cycle analysis. Therefore, taking into account that the differences in the optimisation results are small for the available methods in utility-scale systems, it can be concluded that any method could be used with reliability. The choice of a specific method would depend on the availability of information such as economic revenue data, system cost data and, parameters for calculating the economics of the life cycle.

Table 6. Comparative analysis under the climatic and soiling conditions of Aguascalientes of the existing criteria for optimising cleaning schedules in utility-scale PV systems.

Method ID	Reference	Criterion	Days between cleaning operations (0.21 USD/kWp/cleaning)	Days between cleaning operations (0.03 USD/kWp/cleaning)

1	(Tanesab et al., 2018) [a]	Annual revenue loss due to soiling equals annual cleaning cost	28	11
2	(Besson et al., 2017) [a]	Maximise annual revenue minus annual cleaning cost	31	10
3	(Jones et al., 2016) [a]	Minimise {(annual revenue loss due to soiling plus annual cleaning cost)/(annual revenue)}	25	10
4	(You et al., 2018) [a, b, c]	Maximise net present value	25	10
5	This study [c]	Minimise levelised cost of energy	31	12

[a] Revenue per generated kWh=7 centUSD
[b] Annual escalation rate of revenue per generated kWh=2.5%
[c] System cost=1000 USD/kWp

5. Conclusions

A novel method for optimising the cleaning schedule in photovoltaic systems based on minimising the levelised cost of energy has been developed. The method takes into account the life cycle costs, allowing the influence of the system investment cost on the optimum cleaning schedule to be analysed, and does not depend on economic revenue data, which is often subject to uncertainty. The method has been applied to Aguascalientes, central Mexico, where an experimental characterisation of natural soiling on optimally tilted crystalline silicon modules was performed. The experimental soiling measurements exhibited a soiling rate of -0.16% in the dry season and a stabilization of the soiling losses at 11.2% after 70 days of exposure. The method has been also compared to other existing criteria for optimising cleaning schedules.

The main conclusions of the study are:

- While the cleaning costs play an important role for optimising cleaning schedules, the system investment costs also influence as a second factor. The influence of these investment costs only can be analysed with an optimisation method that considers the whole life cycle of the system, such as the one proposed in this paper.

- Residential and commercial systems minimise the levelised cost of energy without carrying out cleaning operations in Aguascalientes. One cleaning per year would make possible to remove heavy soiling, and avoid permanent damage and contamination to the modules. More cleaning operations are not recommended because of the high cleaning costs.

- Utility-scale systems should be cleaned in intervals between 12 and 31 days in Aguascalientes as a function of the cleaning costs (between 0.03 and 0.21 USD/kWp in this study).

- The comparative analysis under the conditions of Aguascalientes to other existing criteria to optimise cleaning schedules for utility-scale systems revealed that every method gives similar results, with a maximum difference of 6 days in the cleaning schedule. However, the methods require different information to be implemented and, therefore, the choice of a suitable method depends on the data available in each specific project.

The methodology proposed in this paper could be adapted to other locations with different climatic, soiling and, economic conditions. However, in the current study, some simplifications in the energy yield calculation have been considered because of the peculiarities of the typical conditions in Aguascalientes, where the dry and wet seasons are clearly differentiated, the dry season has very scarce rainfall and, the wet season has frequent storms typically every day. Other climates would require a more in deep analysis of the soiling rate seasonal variability and advanced rainfall forecasting techniques.

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