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Modeling soiling losses for rooftop PV systems in suburban areas with nearby forest in Madrid

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Particle deposition on the surface of modules in PV systems produces energy output losses with an impact that highly depends on the meteorological and climatic conditions. This work presents the characterization of soiling losses for a suburban forest area in Madrid focused on rooftop PV systems. The soiling loss measured in the testing system can reach around 6%/day for a tilt angle of 8° during summer. Models assessment is also presented and analyzed here using two available soiling models from the well-known pvlib package. The use of the models is not straightforward and some assumptions and recommendations are also presented in this work to produce the best predictions. The applicability of physical models to suburban areas, particularly in large cities in Europe, is remarked by the availability of air quality monitoring ground stations. These results will enhance future studies on the potential impact of soiling in European cities that will help to the distributed PV systems growth and penetration.

1. Introduction

Photovoltaics penetration in the energy mix is growing faster and globally. However, the PV landscape is foreseen to change, since while utility-scale PV systems have been dominating the market, distributed PV systems are becoming more relevant in many countries [1]. Thus, photovoltaic systems in buildings is an effective and sustainable means of producing renewable energy on site [2]. Especially in urban areas, roof surfaces are increasingly becoming PV roofs and improving the energy self-sufficiency of buildings, which helps the reduction of the greenhouse gases emission in cities. While Building Integrated Photovoltaics (BIPV) refers to the photovoltaic modules and systems substituting building components [3], Building Applied Photovoltaics (BAPV) consists in the attachment of PV modules to existing buildings. BIPV is the ideal solution for new buildings and retrofits [4], where PV modules play a constructive role in façades or roofs, but BAPV can be an interesting alternative for existing buildings not needing an envelope renovation. Both BAPV and simplified BIPV, using conventional PV modules with dedicated mounting structures, have experienced positive developments in numerous countries in 2019 [1].

The accumulation of dirt, dust, pollen and other environmental contaminants on the glazing surfaces of the PV modules reduces the energy conversion efficiency due to the reduction of the effective incoming irradiance. This effect, referred to as soiling, is a complex physical-chemical phenomenon influenced by numerous factors acting on different size and time scales and several models to estimate soiling losses can be found in the literature [5–7]. A thorough overview of published PV soiling models until 2017 can be found in recent literature [8]. A detailed revision of soiling can be found in the recent work of Isle et al. [9]; they provide an in-depth

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understanding of the soiling processes, the role of the adhesion forces and self-cleaning by wind under arid and semi-arid climatic conditions where soiling is mainly produced by mineral dust. Although every PV system undergoes some energy loss due to soiling, PV facilities running in areas exposed to high air concentrations of blown mineral dust, sea salt mist or anthropogenic particulated pollutants become especially affected by soiling issues. For instance, in Egypt, a 1-year-exposed dusty module and a 2-month-exposed dusty module produced 35% and 25% less energy than a clean PV module, respectively [10] and in Saudi Arabia, PV modules exhibited power output reductions of about 50% after being left unclean for eight months and about 20% after a single dust storm event [11]. In comparison, the performance loss due to long-term degradation processes would be of minor significance, with power degradation annual rates of 1.08–1.22% being reported for crystalline silicon modules after 25 years operating in hot dry deserts [12,13]. Thus, the degree of soiling has an important impact on the yield assessment and so does the uncertainty in evaluating the typical soiling losses [14].

When installed in buildings, the PV modules' position is constrained by the building geometry. This frequently forces these PV modules to have tilts and orientations far from the optimal ones, in contrast to the ground-level PV plants. One of the consequences of the varied positions of modules in BIPV or BAPV systems is the different amount of soiling their surfaces accumulate, which is strongly affected by the tilt angle and the distance of the PV modules to the ground. Improving soiling forecasting would help to better decide on a suitable cleaning schedule and to upgrade PV energy simulation models and tools, which should include the impact of soiling as one of the causes of PV losses, named as soiling loss (*SL*) [9,15–21]. Although the influence of soiling on the PV performance has been extensively reported in the literature, this work takes a further step towards assessing *SL* forecasting.

The modeling options for PV systems have spread with the availability and continuous improvement of open-source or free tools. System Advisor Model (SAM) and pvlib are two of the most widely used tools for modeling the performance of PV systems [22,23]. These models estimate the efficiency reduction of the power output due to soiling by means of a derate factor that reduces the effective irradiance. In the case of the pvlib package, there are a lot of additional functions and models for dealing with different simulation steps, such as models for solar irradiance, spectral effects, solar tracking and soiling [24,25]. These particular features give great versatility to the pvlib package in modeling the performance of the PV systems. However, the use of these additional models is not always straightforward and additional knowledge and research are convenient for obtaining reliable results.

This work presents on the one hand the results of the soiling losses measured in both commercial multi-crystalline silicon PV modules and glass coupons during one year of testing in a rooftop site in a suburban area with nearby forest in Madrid (Spain). In addition, two PV soiling models, which are included in pvlib, have been used to evaluate the modeling capability against the experimental measurements. Daily soiling losses up to around 6% have been observed during summer (after over 50 days without any precipitation) and about 2% during winter. Finally, one of the main novelties in this work are, in addition to the soiling experimental characterization, the lessons learned in the use of the models; particularly, the relative influence and impact that some of their main input parameters have on soiling, namely the deposition velocity of the airborne particles and the minimum amount of daily rainfall to clean the modules (cleaning threshold), and the approaches for estimating them as well. The capability of modeling the soiling from monitored particulate matter concentrations is highly interesting for PV penetration in suburban and urban sites, since there are many cities in Europe (like the Madrid case) with a network of air quality stations monitoring these particles.

2. Experimental setup

Two different experimental approaches have been used for characterizing the soiling losses in the PVCastSOIL project: an electrical setup that uses PV modules to explore the electrical loss and a soiling test bench that exposes glass coupons to estimate the optical transmittance loss underwent by the transparent covers of the nearby modules.

The experimental methodology for performing electrical measurements consists in the comparative study of the performance of similar PV modules under the same working conditions except soiling. The setup includes the PV modules under test and equipment to measure different meteorological parameters and the I–V curves of each PV module. These curves are taken for each module with a PVPM2540C (PVE Photovoltaik Engineering) I–V tracer connected to a multiplexer, together with the PV module temperatures and the most relevant meteorological variables. The electrical parameters such as the maximum power (P_{max}) and the short-circuit current (I_{sc}) have been extracted from the I–V curves. The in-plane irradiance has been measured with six crystalline silicon PV reference cells distributed along different points of the planes of the PV arrays to serve for filtering data gathered under non-homogeneous irradiance conditions. There are three multi-crystalline silicon PV modules at 8° tilt and another three ones at 22°, all of them being south-oriented. At the beginning of each monitoring period, all the PV modules were cleaned. Then, once a week only one of the two modules per group (i.e. same tilt) was cleaned, serving as the two clean references. The so-called PVCastSOIL testing facility is set at CIEMAT's headquarters in Madrid, Spain (latitude 40.41N, Köppen climate type Csa), on the flat rooftop of a 10 m high building. Nearby, there is a park area with conifer trees and there are also some paved roads, typical characteristics of many residential areas in the surroundings of Madrid, where there are more green spaces and less building density than in the city center. A picture of the small rooftop PV system used to monitor the soiling losses at two different tilt angles at CIEMAT is shown in Fig. 1.

Concerning soiling monitoring through optical measurements, a soiling test bench was installed to allow the long-term exposure of a large number of glass coupons. Soda lime glass coupons of dimensions 10 cm × 15 cm were placed there and, as a general rule, the exposed glass coupons were collected twice a week in order to characterize them optically in both "dirty" and "clean" states. That is, the glass coupons were analyzed both after cleaning their rear face with soft laboratory paper dampened with ethanol ("soiled coupons") and after washing them with water and a soft sponge and letting them dry ("clean coupons"). Hemispherical transmittance measurements at near-normal incidence were performed using a Perkin Elmer Lambda 900 UV/VIS/NIR spectrophotometer equipped with a 150-mm-diameter integrating sphere. Hence, for each glass coupon, the optical soiling loss was derived by measuring its "dirty state" transmittance spectrum (to account for non-homogeneous soiling patterns, four measurements corresponding to four different sample points were averaged to obtain a representative transmittance curve), normalizing it with respect to its "clean state" transmittance spectrum, and finally averaging the transmittance value for the wavelength interval from 340 nm to 1200 nm. Fig. 2 shows a picture of the structure hosting the glass coupons and an example of two soiled coupons.

In addition to the electrical and optical measurements, standard meteorological measurements (e.g. ambient temperature, relative humidity, wind speed and direction, and rainfall) were collected

Fig. 1. Picture of the PVCastSOIL facility in the rooftop of one building at CIEMAT.

both on the rooftop and in a nearby water tower behind the building.

Moreover, particle matter concentrations (PM2.5 and PM10) have been measured in an air quality station equipped with optical particle counters at CIEMAT. $PM_{2.5}$ includes all particles with diameters of less than 2.5 μm and, correspondingly, PM_{10} includes those of less than 10 μm. The Madrid City Hall has a network of air quality stations whose data are openly available. One station from this network (Casa de Campo) is placed about 5 km away from CIEMAT in a similar forest environment; its data have been used to fill occasional gaps found in the CIEMAT database of airborne particulate matter concentrations.

3. Description of models for estimating the soiling ratio

Two different models for estimating the soiling ratio, implemented in the pvlib tool, have been analyzed and evaluated with the experimental measurements. First, the Kimber model [6] is a very simple model that assumes a constant rate of soiling between two rainfall cleaning events. The input to the model contains four main elements: the accumulated rainfall (mm), the soiling rate, the cleaning threshold and the grace period length. The soiling rate is an empirical parameter which refers to the fraction of energy loss per day. The cleaning threshold is the minimum amount of daily rainfall required to clean the modules. Finally, the grace period is the number of days assumed without significant soiling after a rainfall event. Therefore, the Kimber model imposes a constant soiling rate after the grace period until the next rain event reaching the cleaning threshold occurs. These parameters are purely empirical and depend on both the geographical region and the soiling environment type; the authors reported soiling rates from 0.1% in rural areas to 0.3% in suburban and urban ones [6].

Secondly, the HSU (Humboldt State University, CA USA) model relies on the assumption that the soiling rate is determined by the accumulated rainfall (mm), the airborne particle matter concentration (both $PM_{2.5}$ and PM_{10}) and the tilt angle of the exposed PV module [7]. Hence, the soiling loss is calculated by,

$$SL = 1 - 34.37\ \mathrm{erf}\left(0.17\ \omega^{0.8473}\right) \quad (1)$$

where ω is the total mass accumulation (g/m^2).

The total mass accumulation is the integral in time of the deposited mass rate,

$$\omega = \int (\upsilon_{PM10} C_{PM10} + \upsilon_{PM2.5} C_{PM2.5})\ cos\beta\ tdt \quad (2)$$

where υ_{PM10} and $\upsilon_{PM2.5}$ are the deposition velocities for airborne particles with aerodynamic diameters less than 10 and 2.5 μm, respectively; C_{PM10} and $C_{PM2.5}$ are the corresponding mass concentrations of these airborne particles and β is the tilt angle of the PV module.

Likewise the Kimber model, the HSU model needs a cleaning threshold parameter to determine the minimum accumulated rainfall required to completely clean the module.

The deposition velocities for airborne particles are affected by the wind speed, the particle properties and size, and other factors that may make difficult to calculate theoretically [26]. The

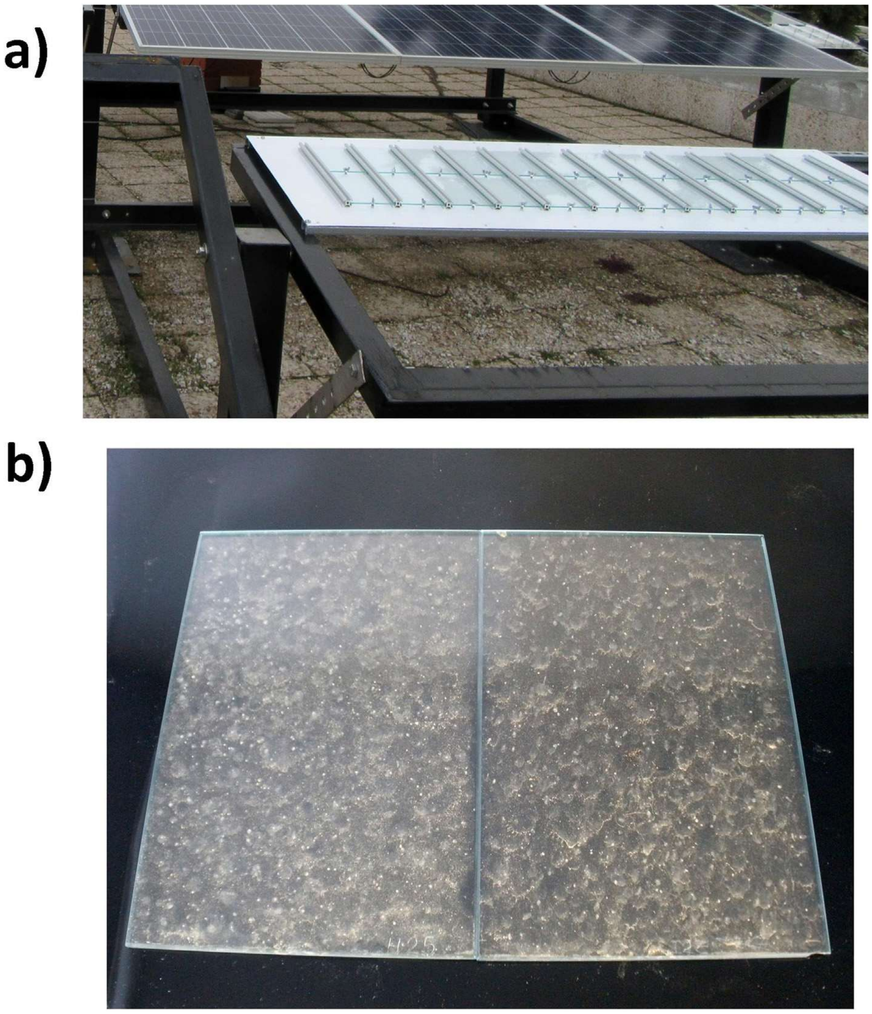

Fig. 2. Set of glass coupons for measuring the optical the soiling loss (a). Image of two soiled glass coupons (b).

deposition velocities can be introduced in the HSU model as constants or can be calculated as a function of the meteorological conditions (i.e. wind speed and ambient temperature) using the Zhang model for dry deposition velocity which is based on the Slinn's model developed for vegetated canopies [27,28]. In the HSU model implementation in pvlib it is recommended to use the gravitational settling velocity (0.0009 m/s and 0.004 m/s for $PM_{2.5}$ and PM_{10}, respectively). However, it should be remarked that these values are significantly lower than dry deposition velocities reported in recent works for forest areas [29–31].

4. Methodology for measuring the soiling loss

The soiling ratio, and thus the soiling loss, has been estimated here from a metric for performance index (PI_{Isc}) of the soiled and the reference modules. Since I–V curves are being continuously monitored in the experimental facility, the performance index computed for soiling estimations is calculated from the temperature-corrected short-circuit current. The short-circuit current of a PV module is proportional to the irradiance so that it seems to be the best parameter to characterize soiling losses, since soiling implies a reduction in the effective irradiance [32,33]. Therefore, the performance index computed from the short-circuit current is defined, in analogy with the performance ratio, as,

$$PI_{Isc} = \frac{1000\, I_{sc}\, (1 - \alpha_{SC}(T_{mod} - 25))}{I_{sc}^{STC}\, G_{POA}} \tag{3}$$

where I_{sc} and I_{sc}^{STC} are the short-circuit currents of the module at environmental conditions and at STC (Standard Test Conditions, 1000 W m^{-2} and 25 °C), respectively; α_{SC} is the temperature coefficient of the short-circuit current; T_{mod} is the module temperature; and G_{POA} is the plane of the array irradiance.

Therefore the soiling loss (SL) can be defined from the corresponding performance index of the soiled (PI_{Isc}^{Soiled}) and reference modules (PI_{Isc}^{Clean}) as,

$$SL = 1 - \frac{PI_{Isc}^{Soiled}}{PI_{Isc}^{Clean}} \tag{4}$$

The situation of the experimental facility (i.e. a rooftop with a few large trees nearby that shade the modules partially during the morning hours) somehow limits the computation of the daily soiling losses. Therefore, in order to avoid measurements with partial shading issues of the single modules, the daily soiling loss is computed by averaging the performance index of the instantaneous

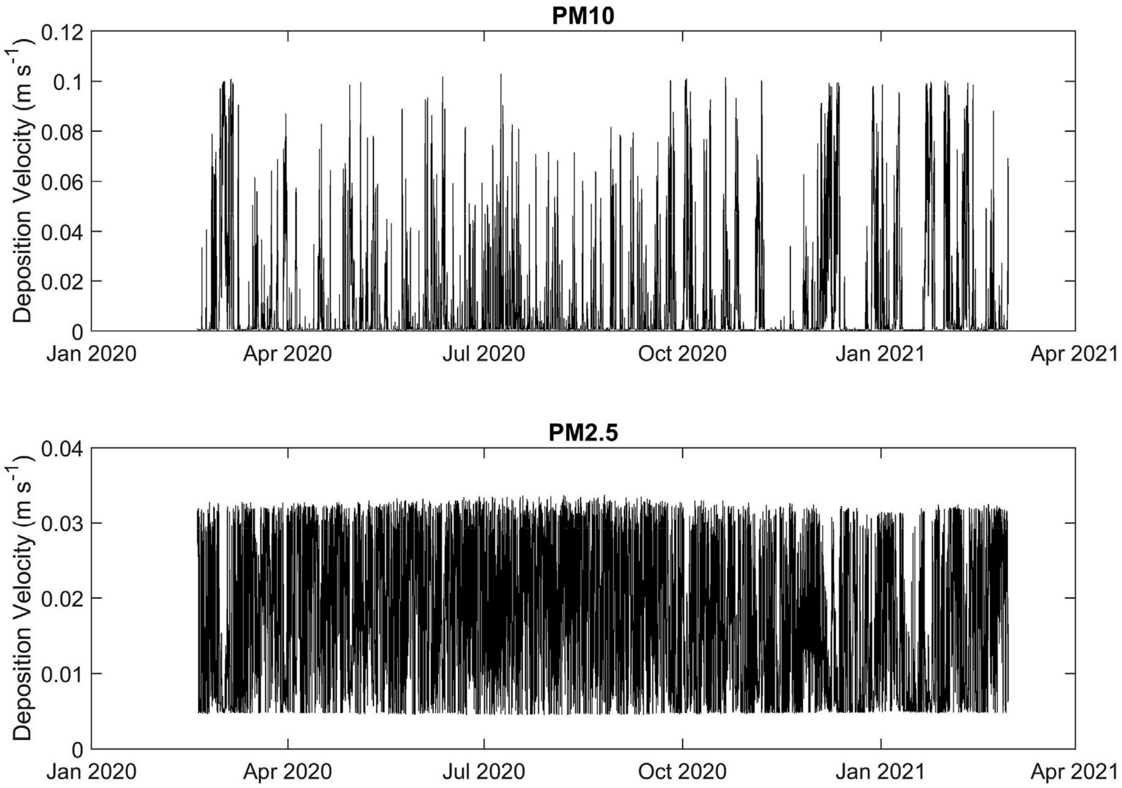

Fig. 3. I–V curves of clean and soiled PV modules on July 4th, 2020.

measurements in the time range of 12–18 h (true solar times).

In the case of the optical measurements taken in the glass coupons the soiling loss is computed through the broadband transmittances of soiled (T_{Soiled}) and clean (T_{Clean}) coupons by Ref. [34],

$$SL = 1 - \frac{T_{Soiled}}{T_{Clean}} \quad (5)$$

5. Results

The experimental campaign of soiling monitoring for silicon modules tilted 8° and 22° lasted from February 2019 until end of March 2021. Fig. 3 shows the I–V curves of soiled and cleaned modules for three instantaneous measurements on July 4, 2020, namely during the dry summer season after many rainless days. The daily accumulated soiling loss for that day was 3.0% and 4.6% for tilt angles of 22° and 8°, respectively. It can be observed, that the losses are higher for the modules with lower tilt angles. Furthermore, it can be seen that for higher incidence angles (i.e. lower tilt angles) the soiling impact is higher.

Modeling the soiling loss with the HSU model requires some considerations regarding the deposition velocity. Deposition velocities for $PM_{2.5}$ and PM_{10} along the testing campaign (i.e. from February 2020 to March 2021) have been estimated with the Zhang model, implemented in pvlib, using as inputs the ambient temperature and the wind speed measured at CIEMAT and selecting evergreen land type. Fig. 4 shows the resulting dry deposition velocities computed from the time series of ambient temperature and wind speed monitored at site. Larger variability in the velocities is observed for PM_{10}, which falls in the range 0.01–0.1 m/s, while the range of velocities for $PM_{2.5}$ is narrower (≈0.01–0.03 m/s). These values are notably higher than the default settling velocities (0.0009 and 0.004 m/s for $PM_{2.5}$ and PM_{10}, respectively). Modeling the deposition velocities has significant uncertainties [35]; however, these expected uncertainties do not completely explain the differences between the calculated dry deposition velocities for the test site and the default values from the HSU model. According to the variability and the range of values of the calculated deposition velocities it is expected a more realistic behavior of the HSU model using variable deposition velocities instead of constant default values.

Thus, soiling losses were modeled with the HSU model using the computed deposition velocities and a cleaning threshold of 4 mm. In addition, soiling losses have been also calculated with the Kimber model using purely empiric parameters. The daily soiling loss rate was set empirically to 0.0014 and 0.0018 for the 22° and 8° tilted modules, respectively. The default value recommended in the model implementation in pvlib is 0.0015. The cleaning threshold parameter (i.e. the minimum amount of daily rainfall required for fully cleaning) was set to 4 mm as well. The grace period imposed in the Kimber model was 7 days, since the reference modules in the PVCastSOIL facility were cleaned every week, and such a value has been proposed in previous works [36]. Fig. 5 presents the soiling losses estimated by the HSU and the Kimber models compared to the experimental measurements at the PVCastSOIL facility. A good agreement is generally found in both models. The chosen cleaning threshold of 4 mm seems to fit quite well with the cleaning by rainfall observed in the experimental data, excepting for March 8th 2021 when 4.5 mm of measured rainfall did not result in complete cleaning of the modules. In that period the predicted trend of soiling of the HSU model was quite good compared with the experimental data but it dropped suddenly after the rainfall. This observation is more pronounced in the case of 8° tilt, since not all

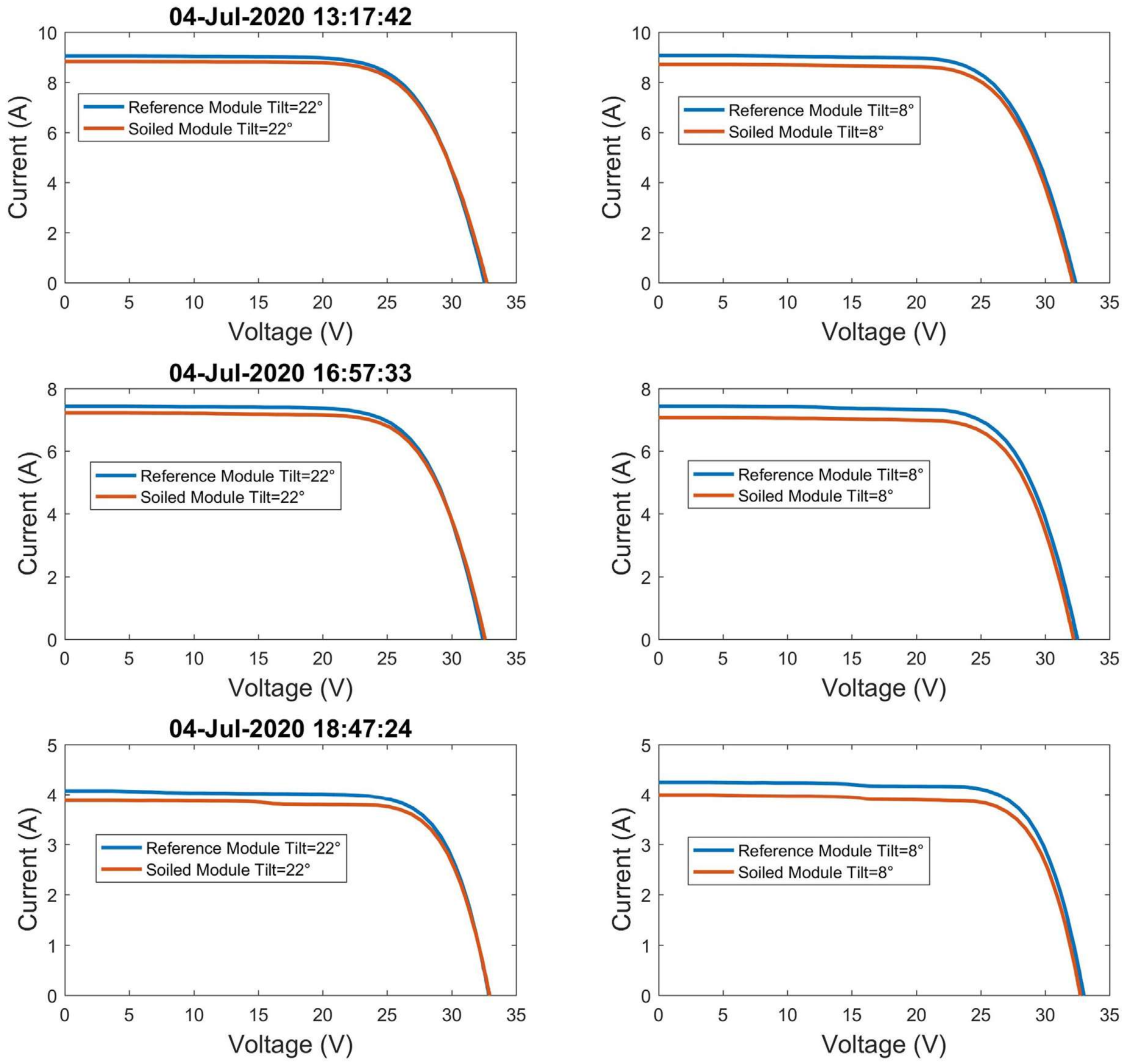

Fig. 4. Calculated dry deposition velocities for $PM_{2.5}$ and PM_{10} estimated from ambient temperature and wind speed monitored at CIEMAT during the testing campaign using the model of Zhang et al., 2001.

the rainfall events resulted in the complete cleaning of the modules.

Fig. 6 shows the comparison of the electrical and optical soiling measurements with the HSU model estimations for the tilt angle 8°. In summer, with less frequent rainfall events registered, the measured daily soiling loss was around 6% and 4% after 52 and 38 days without rain, respectively. A general agreement and a correlation between the electrical and the optical soiling losses can be observed. However, the soiling measurements in the modules exhibit more dispersion than the optical ones, which follow a clearer and more continuous trend in the periods between rainfall events. The agreement of the HSU model with the optical soiling losses in the summer season is remarkable. The larger discrepancies among them occur during periods with frequent rain events below the cleaning threshold (for instance, in December 2020 and January 2021), highlighting the importance of tailoring the cleaning threshold parameter for a good modeling accuracy. On the other hand, a partial cleaning of the modules due to lower daily precipitation amounts is not contemplated by the model, which resets the soiling losses to zero whenever the cleaning threshold is reached, and it could be a limitation in the usage of the model depending on the local meteorology of the site.

6. Conclusions

The impact of soiling losses in PV systems depends on the environmental and meteorological conditions of the emplacement. Proper characterization and modeling of the foreseen losses result in significant benefits that ease the penetration of PV systems and reduce the operating and maintenance costs. In the particular case of small rooftop systems the expected growth of distributed PV, particularly in urban and suburban areas of large cities in Europe, brings up the interest in the suitable characterization and knowledge of the soiling issue. In this work, one year of soiling losses measurements is analyzed for a small facility in a rooftop of a building in a forest suburban area in Madrid. In addition, two available models are assessed with the experimental data.

In modeling the soiling impact of a PV system under continental or temperate climatic conditions, which typically results in moderate soiling compared to harsher conditions such as in arid and

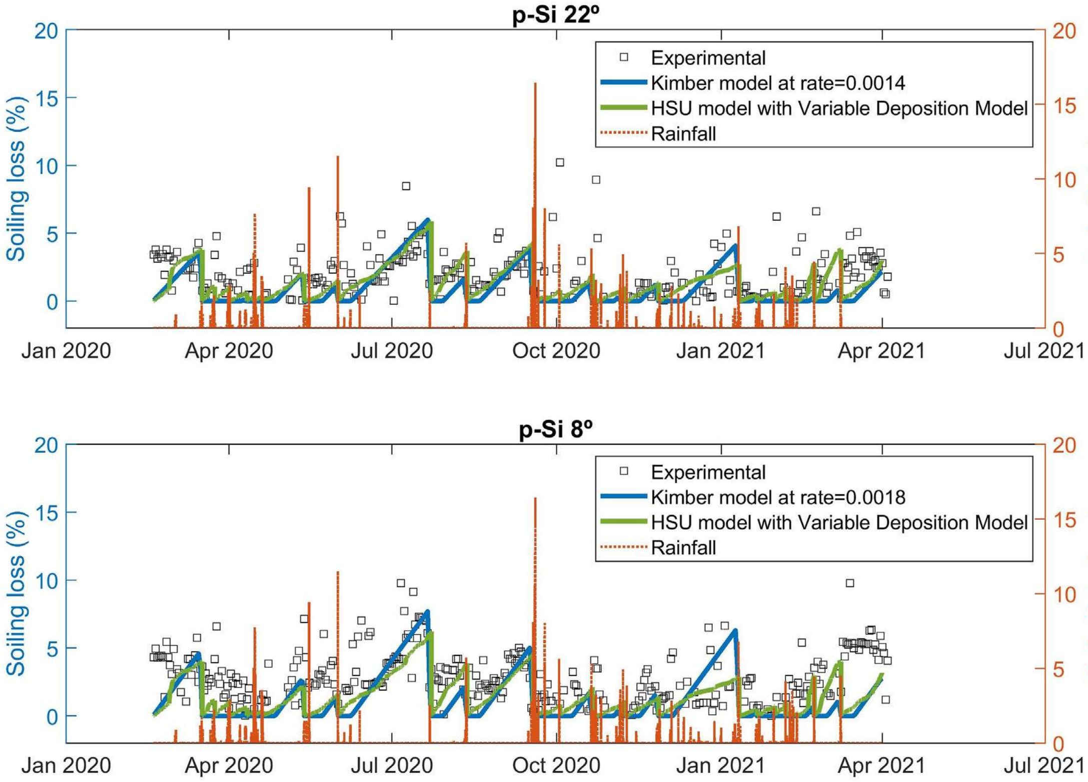

Fig. 5. Assessment of the HSU and the Kimber soiling models with the experimental soiling losses.

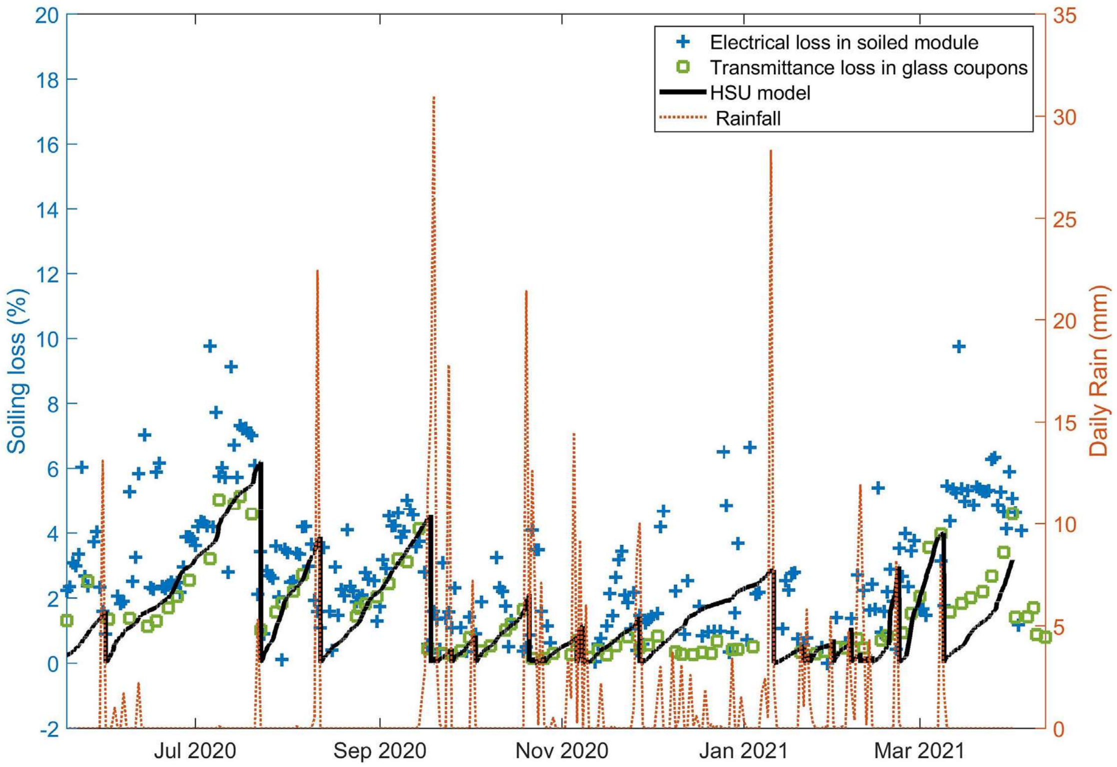

Fig. 6. Comparison of electrical and optical soiling losses measured in the PVCastSOIL facility with the HSU model results for tilt = 8°.

desert environments, the cleaning threshold parameter plays a major role. This parameter is mainly empirical. The observations in the experimental campaign and the results of modeling the soiling loss have determined a value around 4–6 mm adequate for accurately predicting the observations. The soiling models evaluated in this work were the Kimber model (very simple and mostly empirical) and the HSU model (more detailed and including physical fundaments in its formulation). The former is limited to the previous input of the soiling rate, which is stated constant and can be determined empirically from soiling observations. The latter needs the particle matter concentration information as an input. Both models generally showed good results to describe the experimental measurements, particularly in the summer when the highest soiling losses were recorded (i.e. up to around 6%/day).

The analysis of the models presented in this work remarks the need of a particular attention to the deposition velocity. This is a relevant parameter in the HSU model that is variable and may be largely affected by the meteorological conditions (especially by the wind speed). Under the environmental conditions of the suburban area of Madrid the model of Zhang for estimating variable deposition velocities for $PM_{2.5}$ and PM_{10} resulted in very good estimations of the measured soiling loss. One of the main advantages of physical models, such as the HSU, is the availability of using this model in suburban areas of cities in Europe since there are available air quality stations that can provide particle matter concentration data needed by the model.

The work presented here has illustrated the use and the assumptions to be taken in available soiling models, even the simplest ones, for rooftop PV applications.

CRediT authorship contribution statement

Jesús Polo: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Funding acquisition. **Nuria Martín-Chivelet:** Conceptualization, Investigation, Experimentation, Writing – review & editing. **Carlos Sanz-Saiz:** Validation, Experimentation, Writing – review & editing. **Joaquín Alonso-Montesinos:** Validation, Resources, Writing – review & editing. **Gabriel López:** Resources, Writing – review & editing, Funding acquisition. **Miguel Alonso-Abella:** Resources, Experimentation. **Francisco J. Battles:** Validation, Funding acquisition. **Aitor Marzo:** Resources, Validation, Writing – review & editing. **Natalie Hanrieder:** Resources, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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