Optimization of the Tilt Angle of Residential Photovoltaic Panels Considering Dust Accumulation

Anthony S. Curioni, Allan R. Starke and Alexandre K. da Silva

Department of Mechanical Engineering, Federal University of Santa Catarina, Florianopolis, SC 88040-600, Brazil

Abstract

The performance of photovoltaic systems can be significantly affected by the accumulation of soiling on the surface of solar panels, especially in regions with low rainfall. Despite the extensive literature on determining the effect of soiling in solar generation, both experimental and theoretical studies are unable to generalize their findings to different regions. Considering that dust accumulation is reduced with larger tilt angles, and the energy production is significantly impacted by the inclination angles, usually presenting an optimal value for a given latitude, this work seeks to determine the optimal tilt angle of residential solar panels considering the effect of soiling accumulated without cleaning procedures during the analyzed period. A theoretical model is used in which the amount of dust deposited is a function of the tilt angle, exposure time and airborne particles (PM_{10}), directly affecting the energy generation. The energy generated is then calculated for different angles, exposure periods and particulate density, aiming to identify the angle that maximizes energy production for different latitudes. It was found that for low PM10 values, as is the case for most cities in Brazil, the optimal angle for yearly generation is close to the angle of a clean panel, being approximately the local latitude, with the greatest difference in optimal angle being only 7° for a whole year without cleaning or raining.

Keywords: Photovoltaic panels, dust, soiling, energy generation, losses.

1. Introduction

Photovoltaic solar energy has established itself as one of the main renewable sources of electricity generation on the global stage, experiencing impressive growth in terms of generation in the last years (Al-Sharafi et al., 2024). To maximize the energy production of photovoltaic systems, one of the several factors considered is the tilt angle of the solar panels. The tilt angles are traditionally adjusted to improve the capture of solar irradiance throughout the year depending on the latitude of the location, with the value indicated for the optimal angle being approximately the local latitude (Cheng et al., 2009). For example, Kaddoura et al. (2016) determined the optimal tilt angle for various cities in Saudi Arabia based on an experimentally validated theoretical model, demonstrating that bimonthly adjustments can significantly increase the annual energy yield.

However, an additional factor to be considered when optimizing the tilt angle is the influence of dirt — the accumulation of dust, impurities and any sort of particulate on the modules' surface — which significantly reduces the amount of irradiation transmitted to the panel and thus decreases the energy yield (Lu and Hajimirza, 2017). As demonstrated by Hegazy, (2001), increasing the tilt angle of panels results in lower dust accumulation. Therefore, while increasing the tilt angle of a panel to a larger value than the optimal reduces the incidence of solar radiation, it could also reduce the dirt accumulation, resulting in a new optimal tilt angle that maximizes power generation considering both effects.

Several experimental studies have investigated different impacts associated with the accumulation of dust on the performance of photovoltaic modules under different environmental and climatic conditions (Abderrezek and Fathi, 2017; Hammoud et al., 2019; Juaidi et al., 2022; Kalogirou et al., 2013; Mejia et al., 2014; Piliougine et al., 2013; Schill et al., 2015; Urrejola et al., 2016). However, these studies tend to have their results restricted to the location in which they were conducted, due to different radiation conditions, types of dirt, rainfall frequency, and other, which can lead to an overestimation/underestimation of soiling losses (Mejia et al., 2014), making it difficult to generalize their findings to other locations. This is of particular concern in countries of continental dimensions, such as Brazil, being necessary to propose models that can predict such effects in different locations using measured environmental data.

One study of such nature was conducted by Coello and Boyle (2019), which proposed a model for dust accumulation

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over time in terms of airborne particulate matter (PM_{10} and PM2.5), module tilt angle and rain data. This model, although being simple model, demonstrated the ability to accurately estimate soiling. A similar study was conducted by Xu et al. (2017), where a new model was proposed by considering the effect of soiling in the transmittance of the PV panels. It was also able to demonstrate that soiling has no effect on panels temperature.

As could be seen by the works presented above, there is still need for a study that can simultaneously assess the tilt angle effects coupled with soiling modelling for general locations. Therefore, the present work proposes to analyze the influence of dirt accumulation in the optimal inclination angle of fixed solar panels, as illustrated in Figure 1. The goal is to optimize the tilt angle to simultaneously increase the incidence of solar energy and reduce the dust accumulation, resulting in a larger long term energy production, with this study being developed for several cities in Brazil. This approach can provide a suitable solution where periodic cleaning of panels may be impractical or costly, as in rooftop panels, that is, a practical design for realistic operating scenarios where maintenance is limited.

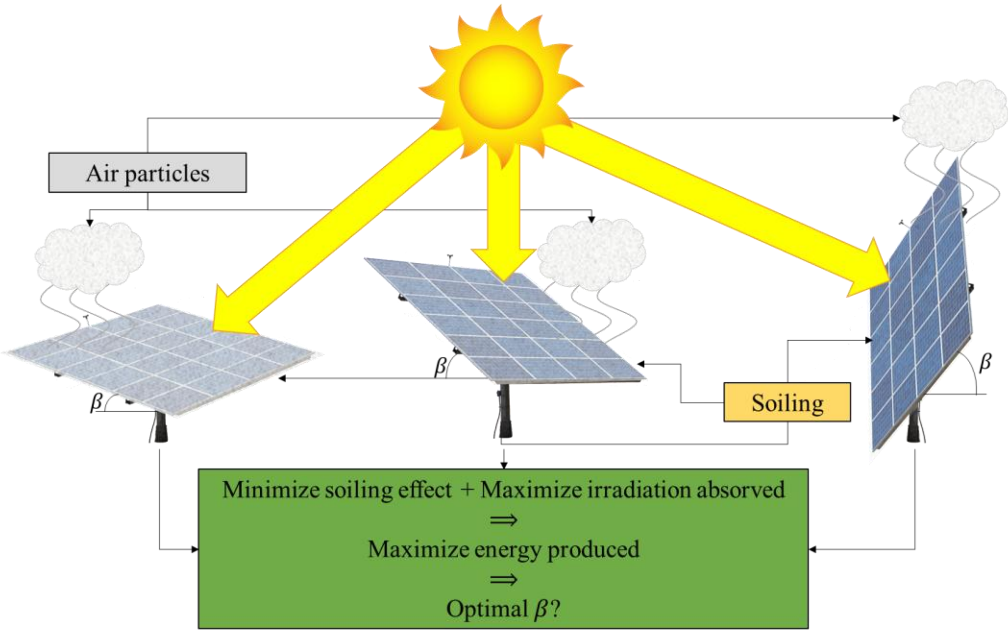

Figure 1: Framework of the present study.

2. Methodology

With the intention of determining if there is an optimal tilt angle for PV energy generation with soiling effects, the following methodology was developed. Different soiling models were coupled to determine the evolution of dust accumulation over time, for diverse locations and its impact on the PV generation. Once the soiling model was developed and meteorological data from Brazil was gathered, a simulated approach was utilized, using open-source python libraries (Anderson et al., 2023), where the energy produced by the panel was simulated for different angles, exposure periods and locations, aiming to analyze the panel behavior under different conditions. The methodology is described in detail in the subsequent sections.

2.1. Soiling model

The first step to build a model that account the soiling losses in terms of the tilt angle is to obtain data of dust accumulation in tilted surfaces in terms of the exposure period. The experimental data published by Hegazy (2001) was used as a reference for this task, which shows the dust accumulation (g/m^2) in terms of the tilt angle and exposure period in glass plates. As can be seen in Hegazy (2001), the dust accumulation is larger with horizontal surfaces as expected, and it significantly reduces with larger tilt angles. Moreover, the results showed an asymptotic behavior of dust accumulation in terms of the exposure period. Therefore, and aiming to obtain a model for the dust accumulation, the data reported by Hegazy (2001) was normalized using the values of 30 days' exposure (yellow curve) for each respective tilt angle, as reference, as shown in Figure 2. This procedure shows that the normalized dust accumulation depends only on the exposure time, presenting almost no influence of the tilt angle.

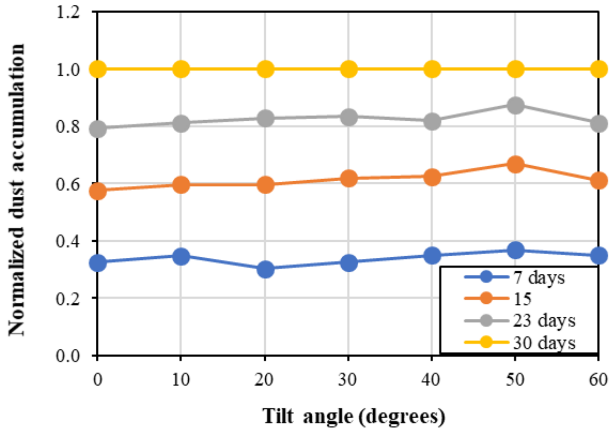

Fig. 2: Dust accumulation overtime at different tilt angles presented by Hegazy (2001) normalized by the values at 30 days exposure.

The average value of the normalized dust accumulation for each exposure time (average value of each colored line in Figure 2b) can be modeled in terms of the exposure time (Δt in days) by the following equation,

$$\tau(\hat{t}) = \frac{a_t \hat{t}}{b_t + \hat{t}}\left(1 - e^{-f_t(\hat{t}+b_t)}\right) + \frac{c_t \hat{t}}{d_t + \hat{t}}, \quad \text{(eq. 1)}$$

where $\hat{t} = \Delta t/365$, and the constants $a_t, b_t, c_t, d_{,t}$ and f_t were determined to best fit the experimental values in Figure 2b. Then, a model for dust accumulation for 30 days of exposure $\left(\mu_{30} \text{ in } (\mathrm{g/cm^2})\right)$ in terms of the tilt angle $\left(\beta \text{ in } (°)\right)$, can be determined by the expression that follows,

$$\mu_{30}(\beta) = a_a \cdot \arcsin\left(\frac{b_a \beta + c_a}{d_a}\right) + \text{Offset}, \quad \text{(eq .2)}$$

where, the coefficient a_a, b_a, c_a, d_a and Offset were determined to fit the experimental values (yellow line) in Figure 2a. Equation (1) and (2) can be combined to calculate the dust accumulation (μ) simply multiplying both, therefore, $\mu = \mu_{30} \cdot \tau(\hat{t})$.

However, this model does not account for the effect of different locations (spatial variability). In order to integrate this effect in the proposed model, the study carried out by Zhang et al. (2017) was used. In this study, the authors demonstrated that annual dust deposition in a horizontal surface $\left(\mu_y\right)$ is correlated with airborne particles in the atmosphere, $\mathrm{PM_{10}}$ (µg/m³), by the following expression,

$$\mu_y(\mathrm{PM_{10}}) = 0.23(\mathrm{PM_{10}})^{1.47}. \quad \text{(eq. 3)}$$

Finally, the final model for the dust accumulation, correlating Δt, β and $\mathrm{PM_{10}}$ is presented below,

$$\mu(\beta, \Delta t, \mathrm{PM_{10}}) = \mu_{30}(\beta) \cdot \tau(\hat{t}) \cdot \frac{\mu_y(\mathrm{PM_{10}})}{\mu_y\left(\mathrm{PM_{10,\mathit{H}}}\right)}, \quad \text{(eq. 4)}$$

where $\mathrm{PM_{10}}$ is the value for the location being studied, $\mathrm{PM_{10,\mathit{H}}}$ is the $\mathrm{PM_{10}}$ value for the location where Hegazy (2001) conducted his study (Minia/Egypt). The value of $\mathrm{PM_{10,\mathit{H}}}$ for Minia/Egypt (155 µg/m³) was reported by Sivertsen and Seoud (2004). The values for the constants of the correlations are shown in Table 1. As goodness of fit of Eq. (1), a RMS value of 3E-33 and a correlation coefficient of $R^2 = 0.7004$ was obtained, while for Eq (2), a RMS value of 1.01E-2 and a correlation coefficient of $R^2 = 0.9994$ was obtained.

Table 1: Value of constants of the proposed model.

Constant	Value
a_t	-0.0261
b_t	-0.1076
c_t	1.9564
d_t	0.0934
f_t	30.0000
a_a	3.1552
b_a	0.5867
c_a	-33.7920
d_a	-33.8463
Offset	2.2620

The final step of the model consists of calculating the soiling losses in PV modules in terms of the dust accumulation. To do so, experimental data obtained from Cano (2011) was used. In this study, the value of energy losses due to soiling were measured for three different angles, shown by the markers in Figure 3, all three for a period of 90 days without cleaning or raining. Through this data, the values of dust accumulation were calculated using eq. (4), allowing a relationship between soiling losses (SL) and dust accumulation (μ) to be found, as follows,

$$SL(\%) = 6.7604 \cdot \mu - 0.2790. \qquad \text{(eq. 5)}$$

The results obtained using Eq. (5) and the data reported by Cano (2011) are also plotted in Figure 3, where a good correlation can be seen.

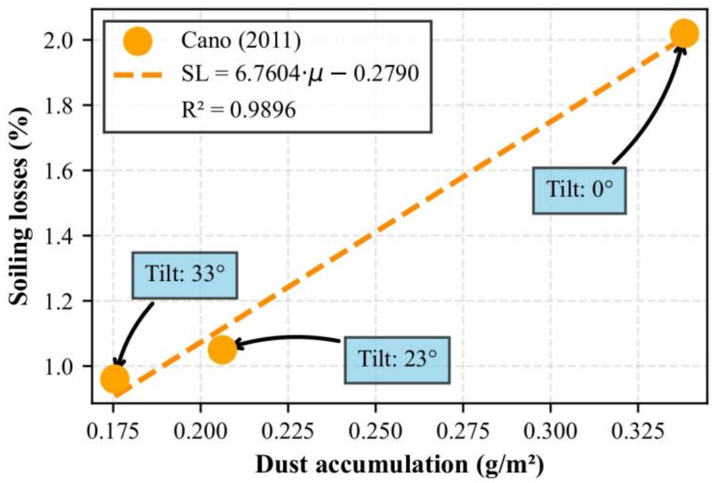

Figure. 3: Correlation obtained between dust accumulation and soiling losses compared with the data of Cano (2011), which are presented by the three circles.

Once the final model is obtained, it can be plotted against the original values as it is shown in Figure 4, on the left. As can be seeing, the correlation fits the data accurately, with a RMS of 0.1 g/m². To evaluate the yearly behavior of the solar panel, it is important that the correlation remains valid over an entire year, even beyond the range of measured data. To ensure this, the values for the correlation were plotted for an entire year to see if its behavior is coherent, as shown in the right frame of Figure 4. It can be observed that the relation between angle and dust accumulation remains decreasing, and the value reaches a limit for longer exposure periods, with both patterns being physically meaningful.

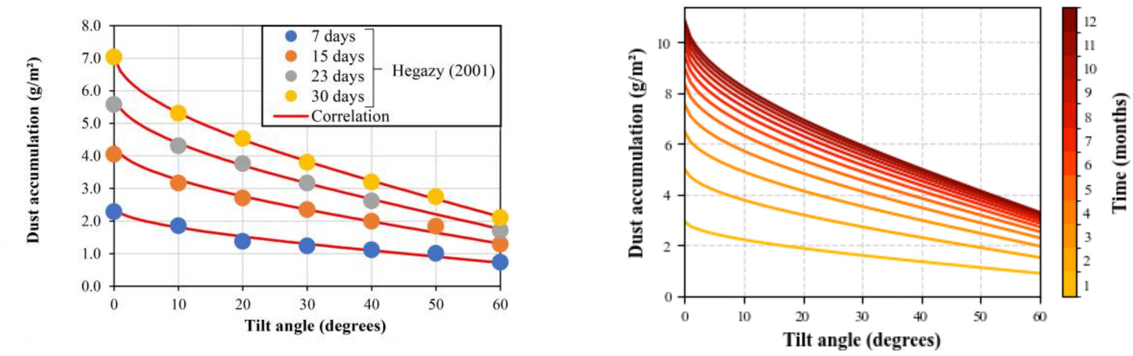

Figure 4: Original data from Hegazy (2001) with develop correlation (left) and correlation data extrapolated for one year (right).

2.2 Energy Generation model and Meteorological/Irradiance data

For modelling the energy generation, the panels were considered with a fixed angle β. It was assumed that the panel would accumulate dust overtime, and this would impact the generation according to the equation in Fig 4. Both the generation and the dust accumulation were calculated daily. Cleaning was not considered in this study. The mathematical model was implemented in python, using the PVLIB library (Anderson et al., 2023), utilizing the ModelChain class to estimate the PV power generation. In this class, a simplified model was chosen, NREL's PVWatts model, only considering the effects of temperature and DC power of the modules at reference conditions, but also considers an inverter efficiency model to estimate the AC power. The parameters utilized in these models are shown in Tab. 2.

Table 2: PV panels and inverter parameters used.

Parameter	Value
Panel DC Power (W)	610
Temperature coefficient (%/°C)	-0.046
Reference temperature (°C)	25
Inverter DC Power (W)	610
Inverter efficiency (%)	96.5

Once the soiling loss model and energy generation model have been defined, one can estimate the PV power production in function of the tilt angle, PM_{10} data, latitude and longitude and solar irradiance. Regarding the solar irradiance a simplified approach was adopted, where the three components of clear sky solar irradiance were calculated using the model proposed by Ineichen (2008) using the latitude and longitude of the selected site. The rationalization for this choice is based on two arguments, (i) the goal is to access the effect of the tilt angle in the soiling effect while also considering the geometric aspect of the incident radiation on the tilted surface, which can be can be assessed using the clear sky irradiance, (ii) using a clear sky model allow us to assess multiple locations without requiring measured irradiance data, which is not extensively available in Brazil. This approach clearly results in overestimated values of the PV power production; however, the optimal tilt angle is significantly more affected by the seasonal effects than the stochastic ones. It is also important to mention that solar irradiance in the tilted plane (I_T) was calculated using the anisotropic sky model of Perez et al. (1987).

In order to analyze the effect of soiling for many regions of Brazil, the cities shown in appendix A were selected as they have a PM2.5 monitoring station (IQAir, 2024). The values of PM2.5 from each city were obtained through the IAQ website (IQAir, 2024). In order to correlate the values of PM2.5 with PM_{10}, the study by Wang et al. (2006) were utilized, were it was showed that the ratio between PM2.5 and PM_{10} was 0.70. For this study, rain was not considered. Finally, Tab. 3 shows a summary of the models used in the present study.

Table 3: Models utilized in ModelChain simulation.

Step	Utilized model	Refs.
Incident irradiance at the module plane	Perez	Perez et al. (1987)
Calculation of the angle of incidence	physical	De Soto et al. (2006)
Solar position	spa (NREL)	Reda and Andreas (2004)
Module model	PVWatts DC	Dobos (2014)
Inverter model	PVWatts AC	
Reflection Losses	ASHRAE	Souka and Safwat (1966)
Calculation of module temperature	sapm	Kratochvil et al. (2004)

3. Results and Discussion

3.2 Results for fixed location

To analyze the effect of soiling, the annual energy generation of the panel was calculated for different levels of PM_{10}, as presented in Figure 6, which also highlights the optimal tilt angle. As PM_{10} increases, the maximum generation decreases, with the tilt angle that results in a maximum annual energy generation shifting to the right, with the optimal angle for a clean panel (29°) being close to the latitude (-27°), as indicated by the literature. For low levels of PM_{10} ($10\ \mu\mathrm{g/m}^3$), the panels behavior closely match a clean panel, with its maximum generation being 99.4% of the maximum generation of a clean panel. For $\mathrm{PM}_{10} = 100\ \mu\mathrm{g/m}^3$, the maximum generation is 78.9% of the clean panel's generation. In terms of optimal angle, the difference between the optimal for clean panel and for 10, 50 and 100 µg/m² are 1, 5 and 14° respectively. Considering that the typical values of PM_{10} for Florianópolis are in the order of 15 µg/m², it can be asserted that the soiling effect does not affects the optimal tilt angle, especially when considering the effects of rain in the soling. However, one important aspect not considered in the present study is that high humidity tends to clog the dust forming a "sticky sludge" (Said et al., 2024). This could potentially keep the dust accumulation to have a near constant value, due to this type of soiling to be harder to remove without active cleaning.

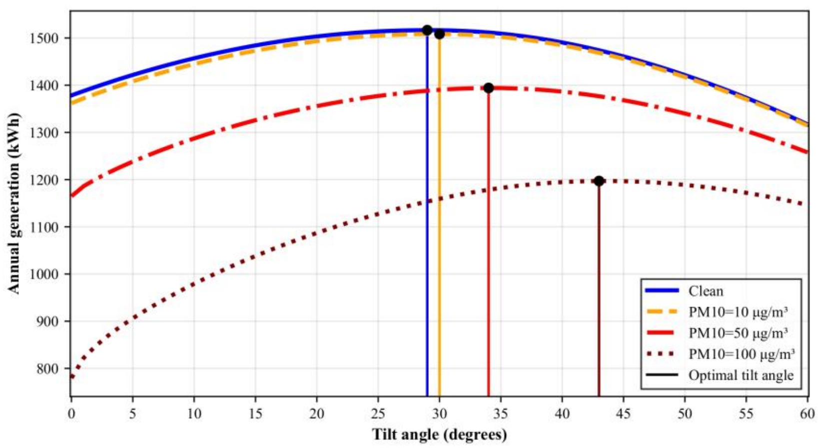

Fig. 6: Simulated annual generation of PV for different angles and levels of PM_{10} for one location (Florianópolis).

Now considering the impact of exposure time, Figure 7 shows the indicated optimal tilt angle for a set uncleaned exposure time. For low values of PM_{10} ($10\ \mu\mathrm{g/m}^3$), the evolution of the angle is no more than 1º in the first year, while for higher values there is a steep rise in the first two months, but with the increase happening at a decreasing rate. These results can also be correlated with rain, as locations with higher rain frequency require angles closer to the optimum for clean panels. It is also clear that for periods longer than a year, there is no significant change in the optimal angle. These results can be applied to determine the optimal angle of any localization simply knowing the expected uncleaned period (either by active cleaning or by rain) and the PM_{10} values for the region.

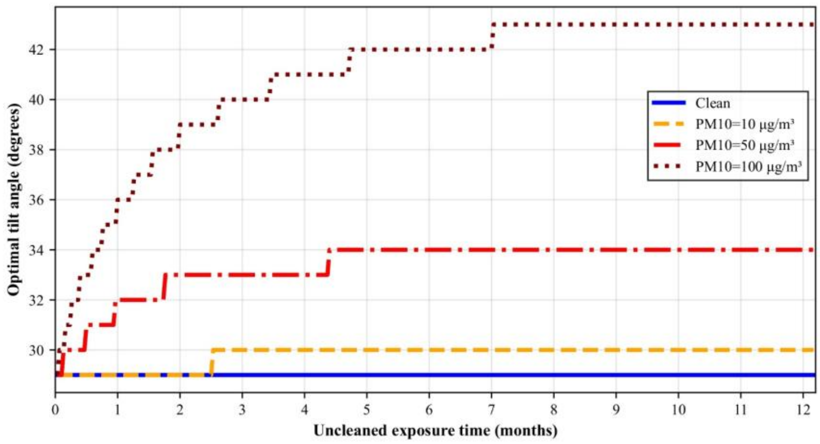

Fig. 7: Optimal angle considering different uncleaned exposure times for different levels of PM_{10} in Florianópolis.

3.3 Results for multiple locations

Figure 8 illustrates the optimal tilt angle for different uncleaned exposure periods for the selected cities, with the green, orange and red bar representing a panel cleaned every day, once a semester and once a year, respectively, while the blue points represent the annual average PM_{10} for each city, with the cities being sorted from lowest to highest PM_{10}. It can be seeing that the PM_{10} levels in Brazil are low, with the highest being 45.7 µg/m². Given this fact, the optimal tilt angle for some cities remains constant even for a year without any cleanups. It interesting to note that, for some cities with lower PM_{10}, like Macapá or Amajari, there is still a small angle increase for longer periods. The reason why this happens is because these cities are close to the Equator, so the optimal angle for clean panel is close to 0°, making the panels in these cities more susceptible to dust accumulation, even with lower PM_{10}.

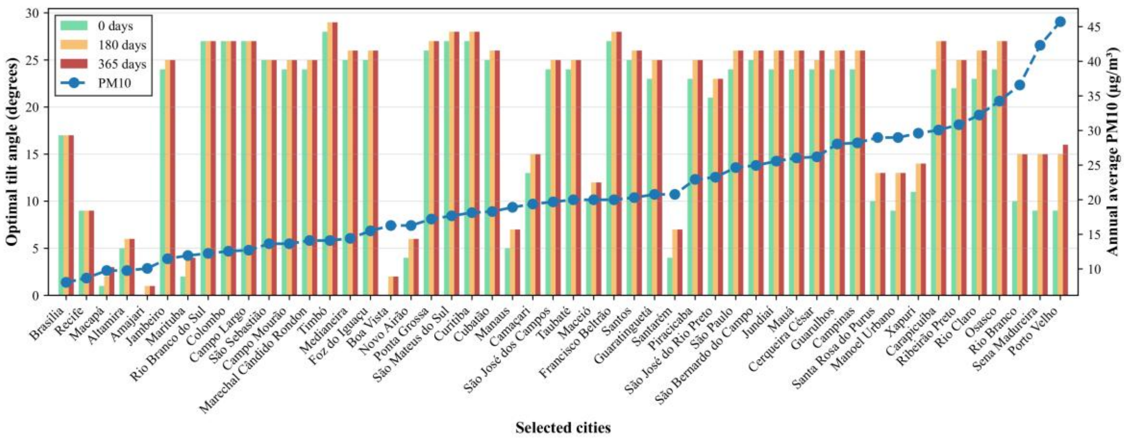

Fig. 8: Optimal tilt angle for selected cities for different uncleaned exposure times and Average Yearly PM_{10} for selected cities.

For cities at the higher end of PM_{10} values, the increase in angle is approximately the same (from 2 to 3°), from Santos to Osasco. The remaining three cities, Rio Branco, Sena Madueira and Porto Velho, experience both lower tilt angles for clean panels due to their latitude and the highest PM_{10} of the selected cities, making their angle increase the most pronounced, with the biggest being 6° for the first 6 months and 7° for one year. Another detail worth considering is that only one of the cities above, Recife, is from the Northeast region, which is a semi-arid region and one where the effects of soiling could be significant. However, Recife is a coastal city, not suffering from soiling, as demonstrated in Figure 8.

4. Conclusions

One of the main contributions achieved of this study is the development of a theoretical methodology capable of estimating the optimal tilt angle for fixed solar panels in any location, incorporating the effects of dirt accumulated over time with airborne particle density, by combining models previously validated in literature. However, comparison with literature indicates the need for experimental validation in order to guaranty model robustness.

The results show that for low values of PM_{10}, the optimum tilt angle will be close to the optimum angle of a clean panel. For $PM_{10} = 10, 50$ and 100 μg/m², the difference between the clean and uncleaned panel tilt angle was 1, 5 and 14°, respectively. The angle increase is greater in the first two months, with its growing decreasing overtime, being essentially constant for periods longer than a year.

Even though higher PM_{10} levels favor higher angles, there are few places in Brazil where this difference is significant, whit the highest angle increase observed being only 7° and many cities having no difference at all. One suggestion of a future study is to analyze the semi-arid regions of Brazil, since these places would be more affected by soiling. Another suggestion is to incorporate rain data in the study, to better justify the choosing of a particular optimal angle.

5. Acknowledgments

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Appendix A: Selected cities

Table 4: Selected Cities for Brazil. PM2.5 values were obtained from IQAir (2024).

City	State	Region	Latitude	Longitude	PM2.5 $(\mu g/m^3)$
Porto Velho	Rondônia	Norte	-8.7612	-63.8999	29.5
Sena Madureira	Acre	Norte	-9.0658	-68.6572	27.3
Rio Branco	Acre	Norte	-9.9747	-67.8104	23.6
Osasco	São Paulo	Sudeste	-23.5329	-46.7919	22.1
Rio Claro	São Paulo	Sudeste	-22.4115	-47.5615	20.8
Ribeirão Preto	São Paulo	Sudeste	-21.1767	-47.8208	19.9
Carapicuíba	São Paulo	Sudeste	-23.5225	-46.8356	19.4
Xapuri	Acre	Norte	-10.6511	-68.4945	19.1
Manoel Urbano	Acre	Norte	-8.8392	-69.26	18.7
Santa Rosa do Purus	Acre	Norte	-9.4256	-70.4869	18.7
Campinas	São Paulo	Sudeste	-22.9099	-47.0626	18.2
Guarulhos	São Paulo	Sudeste	-23.4538	-46.5333	18.1
Cerqueira César	São Paulo	Sudeste	-23.0353	-49.1664	16.9
Mauá	São Paulo	Sudeste	-23.6678	-46.4612	16.8
Jundiaí	São Paulo	Sudeste	-23.1864	-46.8842	16.5
São Bernardo do Campo	São Paulo	Sudeste	-23.6914	-46.5646	16.1
São Paulo	São Paulo	Sudeste	-23.5505	-46.6333	15.9
São José do Rio Preto	São Paulo	Sudeste	-20.8197	-49.3794	15
Piracicaba	São Paulo	Sudeste	-22.7253	-47.6492	14.8
Santarém	Pará	Norte	-2.4411	-54.7083	13.4
Guaratinguetá	São Paulo	Sudeste	-22.8164	-45.1931	13.4
Santos	São Paulo	Sudeste	-23.9608	-46.3335	13.1
Maceió	Alagoas	Nordeste	-9.6658	-35.7353	12.9
Francisco Beltrão	Paraná	Sul	-26.0809	-53.0544	12.9
Taubaté	São Paulo	Sudeste	-23.0264	-45.5553	12.9
São José dos Campos	São Paulo	Sudeste	-23.1791	-45.8872	12.7
Camaçari	Bahia	Nordeste	-12.6975	-38.3244	12.5
Manaus	Amazonas	Norte	-3.119	-60.0217	12.2
Cubatão	São Paulo	Sudeste	-23.895	-46.4253	11.8
Curitiba	Paraná	Sul	-25.429	-49.2671	11.7
São Mateus do Sul	Paraná	Sul	-25.8733	-50.3828	11.4
Ponta Grossa	Paraná	Sul	-25.095	-50.1619	11.1
Novo Airão	Amazonas	Norte	-2.6203	-60.9428	10.5
Boa Vista	Roraima	Norte	2.8235	-60.6758	10.5
Foz do Iguaçu	Paraná	Sul	-25.5469	-54.5882	10
Medianeira	Paraná	Sul	-25.2953	-54.0939	9.3
Marechal Cândido Rondon	Paraná	Sul	-24.5561	-54.0569	9.1
Timbó	Santa Catarina	Sul	-26.8233	-49.2728	9.1
Campo Mourão	Paraná	Sul	-24.0458	-52.3828	8.8
São Sebastião	São Paulo	Sudeste	-23.8003	-45.4072	8.8
Campo Largo	Paraná	Sul	-25.4597	-49.5275	8.2

Colombo	Paraná	Sul	-25.2919	-49.2242	8.1
Rio Branco do Sul	Paraná	Sul	-25.1908	-49.3108	7.9
Marituba	Pará	Norte	-1.3636	-48.3397	7.7
Jambeiro	São Paulo	Sudeste	-23.2508	-45.6908	7.4
Amajari	Roraima	Norte	3.6492	-61.3958	6.5
Macapá	Amapá	Norte	0.0347	-51.0664	6.3
Altamira	Pará	Norte	-3.2033	-52.2064	6.3
Recife	Pernambuco	Nordeste	-8.0476	-34.877	5.6
Brasília	Distrito Federal	Centro-Oeste	-15.7975	-47.8919	5.2