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Estimation of an Optimal PV Panel Cleaning Strategy Based on Both Annual Radiation Profile and Module Degradation

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ABSTRACT This paper addresses a methodology to optimize PV panel cleaning schedule. PV system yield is impacted due to soiling on panel surface. This soiling changes during the system operation as a consequence of environmental conditions. In order to reduce the impact of soiling accumulation, the panel surface must be cleaned. However, cost and frequency of cleaning can affect plant revenue. Therefore, to enhance financial performance, an optimal cleaning strategy must be selected. This strategy depends mostly on energy cost, soiling rate, cleaning costs, and system efficiency. Hence, the model proposed in this work takes into account these variables in order to support the decisions during the assessment of PV yield. The methodology was evaluated through two irradiation profiles with different associated costs. As a result, the methodology made it possible to estimate a cleaning strategy optimizing the incomes under different scenarios.

INDEX TERMS Cleaning schedule optimization, fourier series, solar energy yield, soling ratio.

I. INTRODUCTION

Photovoltaic (PV) generation is considered as a solution to face the issues related to climate change. The use of PV is expected to reduce the emissions produced by electricity generation. Traditional power generation using coal, gas, water, among others, as primary sources is considered as mature and optimized technology. However, the integration of new renewable generation including PV posses challenges during their planning, operation, and maintenance [1].

Accurate estimation of return on investment is a concern of the current planning of PV projects to minimize financial risk. The assessment of return on investment depends on the prediction of power delivery which is influenced by the performance of PV-system. In [2], the factors that influence the system performance are classified by environment, PV system, installation, cost, and miscellaneous. The environmental factors include the solar irradiance, temperature, shades, dust and soiling. As for PV-system factors the I-V characteristics, inverter efficiency, battery efficiency, PV technology, and panel efficiency are considered. The installation factors include cable characteristics, orientation of PV panels, mismatch effects, tracking mechanism, and maximum power point tracker (MPPT). The system cost includes cost of cables and cost of the system. Finally, regarding miscellaneous factors the degradation of PV panels, characteristic resistance, shunt resistance, performance ratio, and maintenance and cleaning are considered. A detailed explanation of the factors is provided in [3]. As various factors influence performance of PV-systems, their assessment can be performed during planning and operation of system or cannot be controlled as shows table 1.

According to table 1, decisions aimed at enhancing the performance of the PV system are made during the planning and operation. In the planning stage, the options with the highest performance(efficiency)/cost relation should be selected for the different components. During the PV-system operation, the factor under control with the highest influence on the performance is cleaning as a consequence of the soiling process [4]. According to [5], the yield loss of PV panel due to soiling can exceed the 1 % per day.

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TABLE 1. Factor that influenced performance of PV-Systems.

Factor	Uncontrol	Planning	Operation
Irradiance	✓		
Temperature	✓	✓	
Shades	✓		
Dust-Soiling rate	✓		
I-V curve		✓	
Inverter η		✓	
Battery η		✓	
PV η		✓	
Orientation		✓	
Mismatch effects		✓	
Tracking		✓	
MPPT		✓	
Cost of cables		✓	
Cost of the system		✓	
Degradation		✓	
Characteristic resistance		✓	
Shunt resistance		✓	
Performance ratio		✓	✓
Maintenance and cleaning			✓

The influence of soiling on PV performance can be reduced by cleaning the panel surface. However, high frequency of cleaning can increase the operation and maintenance costs. To illustrate, the cleaning costs can vary between 0.1 and 10 €m^{-2}, and the estimation of global revenue losses due to soiling is at least 4-7 billion € by 2023 [6]. Therefore, the panel frequency cleaning must be assessed based on energy price, location, PV design, soiling rate, expected power generation, and cleaning cost. For instance, in [4], the influence of moss on performance of PV systems in tropical zones is analyzed. In [7], the results of measuring the PV soiling rate at different locations along Chile are reported; self-cleaning as a consequence of raining and environmental conditions is analyzed. The annual monetary loss was estimated between 3 $/kW$_p$ to 70 $/kW$_p$ depending on the location [7]. In [8], the photovoltaic soiling index is addressed in order to assess the impact of dust on the performance of PV generation. This index considers annual dust accumulation patterns. The financial risk and improvement of the planning of maintenance cost can be assessed based on cleaning optimization.

The optimization of PV cleaning posses a challenge: to estimate the soiling rate, which depends on both location and time. IEC 61724-1 standard [9] recommends monitoring soiling ratio by using two PV devices. In [10], a measuring system composed of hardware and software is addressed to estimate the environmental conditions including soiling. A methodology to estimate soiling loss by measuring PV energy yield is proposed in [11]. In [7], soiling maps along Chile are generated through linear regression by using measurements. Similarly, in [8], the development of photovoltaic soiling maps is proposed. A map of dust intensity around the world is presented in [12]. However, these methods need historical records.

In order to estimate the optimal PV cleaning frequency and its impact on the revenue, different methodologies are proposed in the literature. For instance, a model for estimating the cleaning frequency based on dust deposition velocity is proposed in [13], where the frequency criterion considered is a threshold of 5% of yield loss as a consequence of dust. Therefore, non-techno-economic assessment is considered by this model. In [7], the use of graphical method is proposed, considering historical soiling records and cleaning costs. Additionally, the use of different cleaning frequencies according to season is suggested to enhance incomes. In [14], the optimum cleaning technique is addressed, considering the performance as well as the cost of CdTe-Type modules; both the cleaning technique and frequency were estimated by using PV performance records. An optimization model for bifacial PV modules is addressed in [15] as a mixed integer lineal problem; the objective is to maximize the balance between electricity and cleaning costs. In this model the rain is considered. In [16], a financial model for estimating the optimum cleaning frequency is proposed. This frequency is calculated graphically as the intersection of incomes and expenses. Similarly in [17], an analytic model for computing cleaning cycle considering cost is addressed. In [6], an analytic model for computing the optimal cleaning frequency in a techno-economic way is developed. In the previous works on cleaning optimization cited in this article, it is remarkable that the radiation profile during the year as well as the PV degradation are not considered.

This work proposes a methodology to optimize the PV cleaning frequency considering the annual expected radiation profile, cleaning cost, PV module degradation during time, efficiency of system components, and influence of soiling rate on the PV system yield. To assess the performance of this methodology, a script was developed on python to evaluate the influence of different variables on two radiation profiles in order to obtain the optimal cleaning strategy.

II. BACKGROUND

In this section, the issues related to system efficiency, the influence of soiling on performance, and the life cycle cost associated with PV generation are addressed in order to formulate the optimization problem.

A. EFFICIENCY OF PV-SYSTEMS

The efficiency of a system (η) can be defined as follows:

$$\eta = \frac{P_{out}}{P_{in}}, \tag{1}$$

where P_{out} and P_{in} are the input and output power, respectively. According to [18], the efficiency of an entire PV system (1) is related to cells efficiency (η_1), cell operating temperature (η_2), losses due to Joule effect on conductors as PV-transformer (η_3), efficiency of inverter (η_4), efficiency of the maximum power point tracking (MPPT) (η_5), and finally due to soiling on the panel surface. The efficiency of a PV-system $\left(\eta_{pv}\right)$ can be expressed as follows:

$$\eta_{pv}\left(t\right) = \eta_1\left(t\right) \times \eta_2 \times \eta_3 \times \eta_4 \times \eta_5 \times \eta_6\left(t\right) \tag{2}$$

TABLE 2. Typical efficiency of the components of a PV-System.

Component	Range
Cell	$0.1-0.25$ [18]
T_j	$0.8-0.9$ [18]
Joule Effect	≈ 0.98 [18]
Inverter	≈ 0.95 [18]
MPPT	≈ 0.98 [18]
Soiling	$0.99-0.35$ [4], [12]

it is assumed that η_{pv} varies along time as a consequence of both cell degradation ($\eta_1(t)$) and dust accumulation ($\eta_2(t)$) during the operation of the PV system. Table 2 shows common efficiency values of the different components of a PV system. The efficiency of the cell depends on its technology, including the annual degradation rate, commonly between $0.5\%-1\%$ per year [19], [20]. The temperature of the module (T_j) depends on the cooling conditions, ambient temperature and solar radiation. The Joule effect is a function of the conductor effective area and length as well as of the transformer characteristics, if it is used. The inverter and MPPT efficiency are assumed to be known and given by the manufacturer. Finally, soiling influence on efficiency is relevant to the environment, raining, and PV cleaning frequency. In short, efficiency as a consequence of soiling can be managed during the operation whereas the other efficiency factors can be assessed during PV system planning.

B. SOILING

The process of deposition of dust and other pollutants over a surface can be described by soiling, in this case over PV panels surfaces. Modeling soiling is considered a complex problem given the influencing factors. A complete review about the modeling of this processes can be found in [21]. For instance, in [16], the conversion system efficiency is estimated through two models: Multivariable Linear Regression and an Artificial Neural Network in which dust accumulation and ambient temperature are the independent variables. However, the soiling ratio [11] or efficiency due to soiling (η_6) as a consequence of dust accumulation can be modeled by a black box through a linear [15] or exponential function [17] denoted by:

$$\eta_6(t) = b \cdot \mathrm{e}^{-a \cdot t} \tag{3}$$

where a is a parameter to fit by using historical records of soiling ratio (SR), and b depicts cleaning effectiveness. These constants depend on the environment soiling behavior, tracking system, tilt angle, and effectiveness of cleaning.

C. LIFE CYCLE COST

In order to minimize the financial risk and to optimize the return of the investment, the entire PV system life cycle cost needs assessment. An approach to achieve this objective is to use the total expenditure (TOTEX), which is given as follows:

$$TOTEX = CAPEX + OPEX \tag{4}$$

where CAPEX and OPEX are the capital expenditure and operational expenditure, respectively.

According to sections II-A and II-B, the influence of CAPEX on PV-system efficiency depends on the initial investments on PV panels, inverter and MPPT, conductors, power transformer, among others. Therefore, the CAPEX is a function of characteristics of those components expressed as follows:

$$CAPEX = f(\eta_1(t), \eta_3, \eta_4, \eta_5) \tag{5}$$

OPEX is related to cost to enhance the efficiency (η_6) through a cleaning strategy. This strategy depends on the soiling rate, PV degradation, raining, and both cleaning (u_c) cost and energy cost (E_c). Hence, OPEX depends on both cost and effectiveness of the cleaning strategy as:

$$OPEX = f(\eta_6(t)) \tag{6}$$

Finally, to assess the return on investment, the ROI metric can be used as follows:

$$ROI = \frac{Inc_{PV}(t) - TOTEX(t)}{TOTEX(t)}, \tag{7}$$

where Inc_{PV} are the incomes which depend on PV system yield and energy price. ROI is a function of the energy selling price, solar radiation, cooling conditions, efficiency of components, and initial investments.

III. PROPOSED TECHNO-ECONOMIC OPTIMIZATION MODEL

In this section the proposed techno-economic model for optimizing the cleaning strategy of PV is addressed. This model is based on the methodology proposed in [6], where both a linear soiling model and a constant irradiation are assumed. In the model proposed in this paper, both the exponential behavior of soiling and the expected generation profile during the year are included. In this model time cleaning is not considered.

The optimal cleaning mostly depends on the soiling rate, cleaning cost, and the solar radiation on yield of system. However, the environmental conditions including both ambient temperature and solar radiation vary along time. In order to analytically model the influence of solar radiation on the estimation of PV cleaning strategy, it is appropriate to model the solar irradiation (S) per day. This work proposes the use of the following expression to fit S at day k:

$$S_k = a_0 + a_1 \cos(\omega k + \theta), \tag{8}$$

where $\omega = 2\pi/365$ and a_0, a_1, θ are constants to be fitted by using historical records of radiation. With radiation fitted by (8), the energy production (E_T) of PV-system can be estimated by:

$$E_T = \sum_{t=0}^{N} \sum_{k=t \cdot n_t}^{(t+1)n_t - 1} S_k e^{-\alpha \cdot k} \cdot \eta_1(k) \cdot \eta_2 \cdot \eta_3 \cdot \eta_4 \cdot \eta_5, \tag{9}$$

TABLE 3. Assumed system cost for a PV plant of 100 $\mathrm{MW_p}$.

	Description	Value
PV	469500 Panel 1STH-215-P	100 \$/panel
	MPPT $\eta = 0.98$	10 $\$/\mathrm{kW_p}$
	Inverter $\eta = 0.96$	30 $\$/\mathrm{kW_p}$
	Joule $\eta = 0.97$	20 $\$/\mathrm{kW_p}$
	Other	530 $\$/\mathrm{kW_p}$
Energy cost	e_c	0.07 \$/kWh
Cleanning cost	u_c	1.0 $\$/\mathrm{kW_p}$
Soling Ratio	SR	0.01
Cell degradation	η_1	0.0075 /year

where N is the number of cleanings and n_t is the number of days between cleanings. The optimization formulation is determined by:

$$\max_{n_t} \quad e_c \sum_{t=0}^{N} \sum_{k=t \cdot n_t}^{(t+1)n_t - 1} S_k b e^{-\alpha \cdot (k - t \cdot n_t)} \eta_1(k)\, \eta_2 \eta_3 \eta_4 \eta_5 - u_c N - CAPEX$$
$$\text{s.t.} \quad n_t > 0, \tag{10}$$

where u_c and e_c are the cleaning cost and the energy revenue per kW h, respectively. An analytic solution to the previous optimization problem is addressed in appendix.

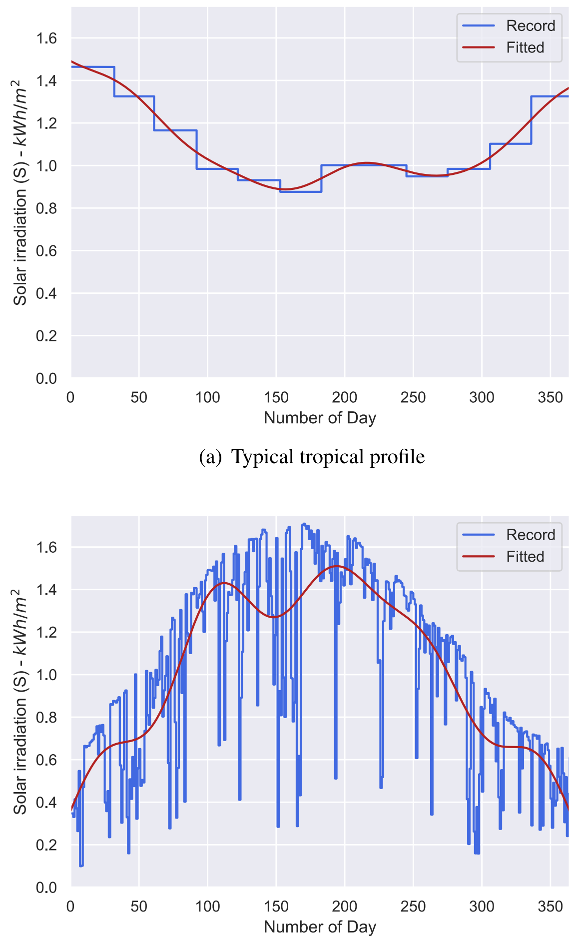
IV. VALIDATION RESULTS

To assess the model proposed in this paper, two annual irradiation profiles are used to estimate an optimal cleaning strategy. One profile shows typical irradiation for tropical zone and the other one is a typical profile in the world north temperate zone. Additionally, these strategies are compared with results to consider an optimal cleaning frequency. This frequency is computed by using the bisection method to solve (10). The optimal cleaning strategy was estimated assuming a warranty period or life cycle of 25 years [4], [19]. Figure 1 shows the two assumed irradiation profiles and fit curves.

The assumed system cost for the assessment is based on [22], considering an installed cost of 1060 $\$/\mathrm{kW_p}$ for an Utility-Scale PV plant as described in table 3. These costs were used to evaluate a PV plant of 100 $\mathrm{MW_p}$ by using the proposed methodology. The constant α of (3) was fitted assuming the SR per 10 d.

A. INFLUENCE OF CLEANING ON INCOMES

Figure 2 shows the influence of using different cleaning frequencies on the total incomes for both assumed irradiation profiles. For both cases, the optimal frequency is approximately 25 d. As can be observed in the plot, lower and higher frequencies reduce the total incomes. For instance, for tropical and temperate zone frequencies it is less than 8 d and 10 d, and higher than 100 d and 80 d it produces negative incomes, respectively.



(a) Typical tropical profile

(b) Typical north temperate zone profile

FIGURE 1. Records and fitted curves of irradiation during the 365 days of a year.

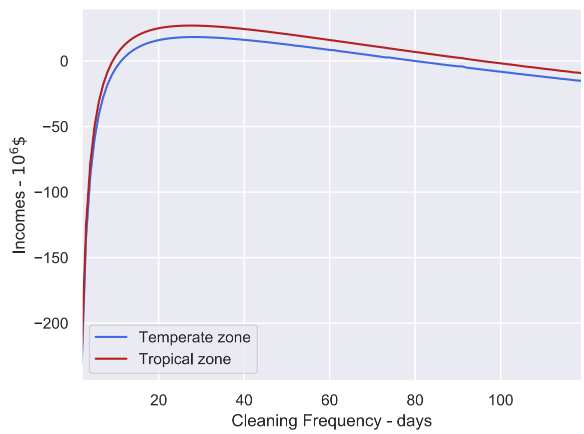
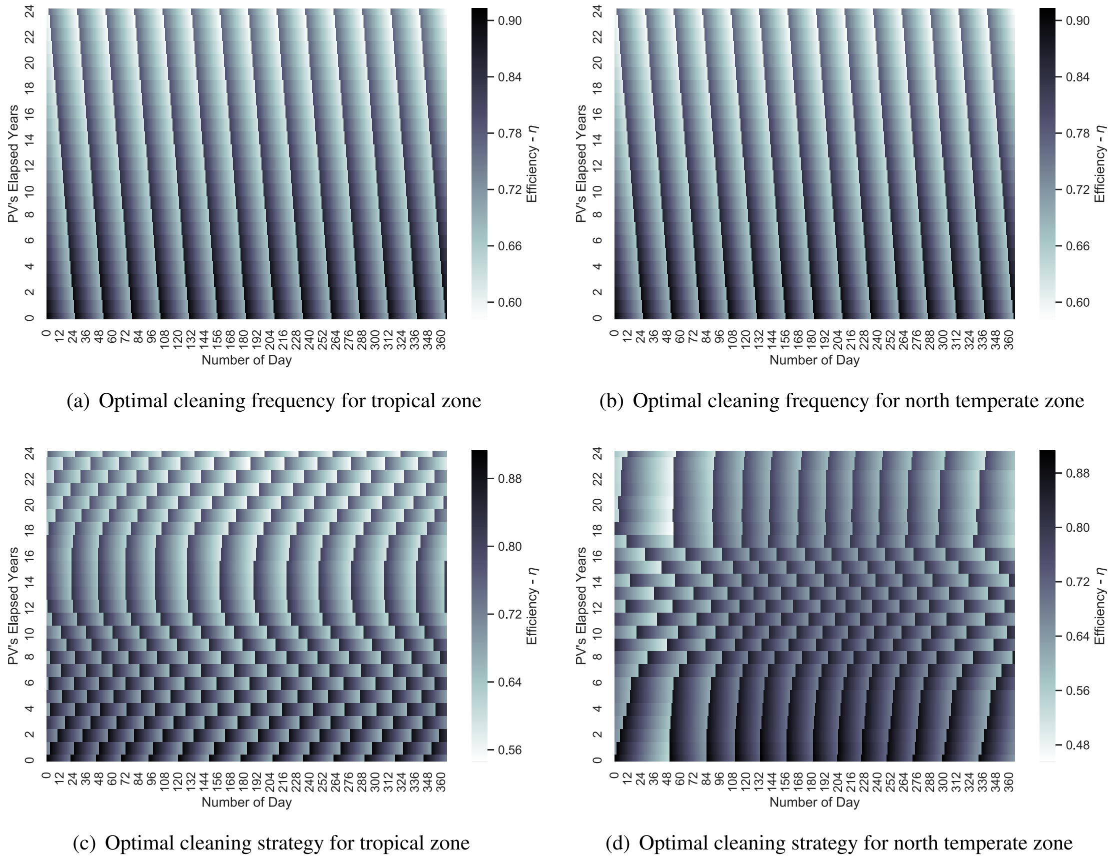


FIGURE 2. Influence of cleaning frequency on total incomes for two irradiation profiles.

B. COMPARISON BETWEEN OPTIMAL CLEANING FREQUENCY AND OPTIMAL CLEANING STRATEGY

Figure 3 shows the comparison on the PV system efficiency when considering two cleaning plans for the tropical zone as



(a) Optimal cleaning frequency for tropical zone
(b) Optimal cleaning frequency for north temperate zone
(c) Optimal cleaning strategy for tropical zone
(d) Optimal cleaning strategy for north temperate zone

FIGURE 3. **Efficiency improvements considering different cleaning plans.**

well as north temperate zone. One plan considers a cleaning strategy computed with the proposed methodology and the other one considers an optimal cleaning frequency. When considering the cleaning strategy, the optimal time between cleaning is influenced by PV cell degradation as a result of a less PV yield, in contrast when considering the optimal cleaning frequency where the time between cleaning is fixed. That can be seen in fig. 3c and mainly in fig. 3d.

Figure 4 shows the assessment of energy production per day during PV plant life. The influence of cleaning on energy production can be appreciated. To use a cleaning strategy instead of a fixed frequency, in periods with higher radiation the number of cleanings is increased in order to increase PV yield, as show in figs. 4(c) and 4(d).

Finally, table 4 summarizes the total incomes in NPV (Inc, assuming a discount rate of 4 %), ROI, and LCOE. To use a cleaning strategy (Str), the improvements compared with an optimal cleaning frequency (F) on Inc and ROI were 0.21×10^6 \$ and 0.5 % for the tropical radiation profile, and 0.64×10^6 \$ and 0.8 % for the north temperate radiation profile, respectively.

C. SENSIBILITY ASSESSMENT

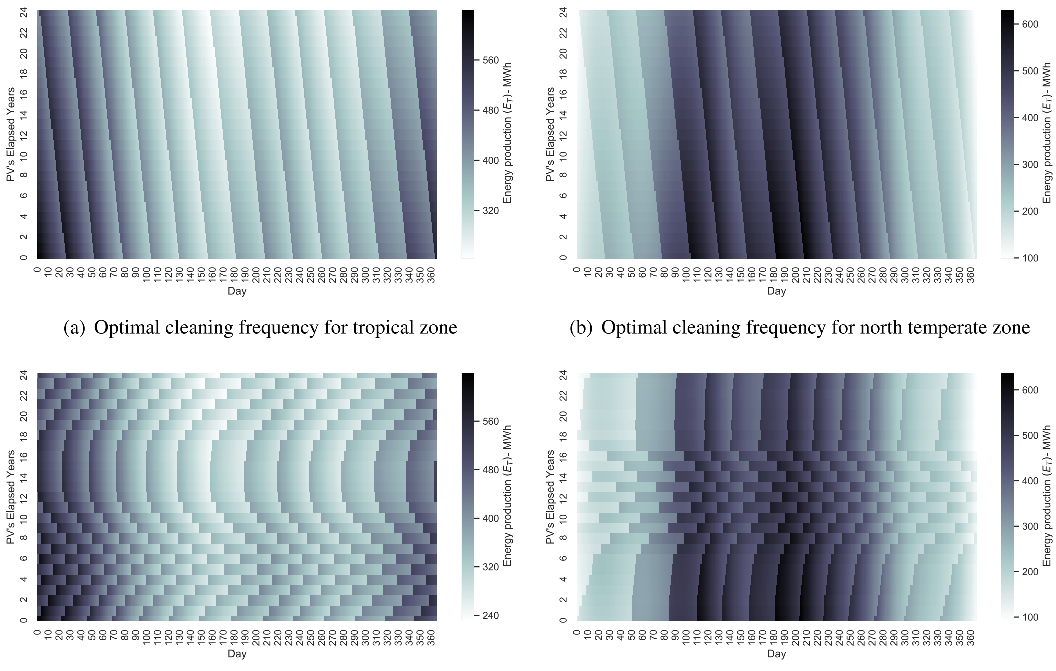
In this section, a sensibility analysis is performed using values of energy revenue of 0.05 \$/kWh and 0.08 \$/kWh for different values of soiling ratio. This aims to estimate the total incomes for both irradiation profiles through an optimal cleaning frequency and an optimal cleaning strategy. Figure 5 shows the assessment; the estimated improvements in using an optimal cleaning strategy are remarkable. This strategy was computed with the proposed methodology. The improvements were higher for high soiling rates and low energy prices.

TABLE 4. **Cleaning strategy comparison using different radiation profiles.**

Profile	Inc.-NPV 1×10^6 \$		ROI %		LCOE \$/kWh	
	Str.	F	Str.	F	Str.	F
Tropical	28.08	27.87	22.2	21.7	0.037	0.037
N. Tem	19.64	19.0	15.6	14.8	0.039	0.039

D. CLEANING TECHNOLOGY ASSESSMENT

In order to evaluate the proposed algorithm in making decisions, the automatic, semi-automatic, and manual cleaning technologies were assessed. The simulation was performed by assuming an increase by technology of 35 %, 10 %, and 0 % in CAPEX, and cleaning cost of 0 $\$/kW_p$, 0.5 $\$/kW_p$, and 1 $\$/kW_p$, respectively. Figure 6 shows the incomes by technology considering different soiling ratios. The incomes



(a) Optimal cleaning frequency for tropical zone

(b) Optimal cleaning frequency for north temperate zone

(c) Optimal cleaning strategy for tropical zone

(d) Optimal cleaning strategy for north temperate zone

FIGURE 4. Influence of cleaning on energy production for the 365 days of a year during the PV plant life.

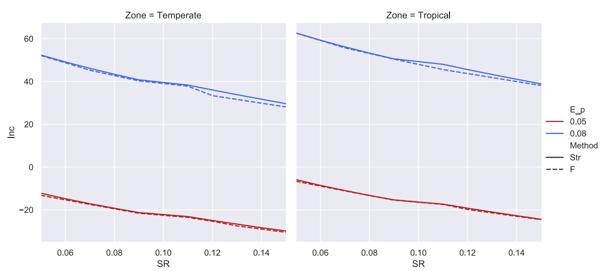


FIGURE 5. Assessment of total incomes in 1×10^6 \$ for different soiling ratios and energy produce revenue using an optimal cleaning frequency and strategy.

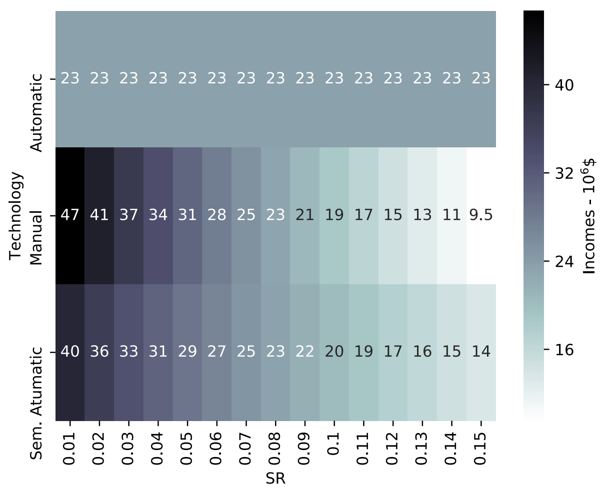


FIGURE 6. Total incomes estimated for three cleaning technologies considering different soiling ratios.

were computed by estimating the optimal cleaning strategy. As a result of this assessment, the automatic cleaning leads to the highest incomes for high dust accumulation or soiling and the manual cleaning has a better financial performance for low soiling ratios as expected. However, these decisions depend on the CAPEX and OPEX cost associated with each technology. A similar evaluation can be performed to assess equipment efficiency and cost.

V. CONCLUSION

The proposed procedure for estimating the optimal cleaning strategy makes it possible to enhance total PV plant incomes. This strategy uses the revenue by energy produced, capital expenditures, efficiency of different PV components, module degradation, soiling ratio, irradiation profile, and cleaning cost. The irradation profile during a year was fitted through the Fourier series. An analytic expression was addressed to estimate the optimal cleaning strategy.

The methodology proposed can be used to assess different options when making decisions such as cleaning technologies, components efficiency, among others. The results depend on both the economic and technical information used as an input to the model. Therefore, uncertainty in the inputs must be considered in order to assess risk.

APPENDIX

Using (8) which describes the energy produced by a PV-cell and (3) which models loss of yield due to soiling, the series (9) can expand as follows:

$$E_T = \eta \left(\sum_{k=0}^{n-1} (a_0 + a_1 \cos(\omega k + \theta)) e^{-\alpha \cdot k} \right.$$
$$\left. + \sum_{k=n}^{2n-1} (a_0 + a_1 \cos(\omega k + \theta)) e^{-\alpha \cdot (k-n)} \right.$$

$$+ \sum_{k=2n}^{3n-1} \left(a_0 + a_1 \cos\left(\omega k + \theta\right)\right) e^{-\alpha \cdot (k-n)} + \dots$$
$$\left. + \sum_{k=T-n}^{T-1} \left(a_0 + a_1 \cos\left(\omega k + \theta\right)\right) e^{-\alpha \cdot (k-n)} \right) \quad (11)$$

where $\eta = \eta_1 \times \eta_2 \times \eta_3 \times \eta_4 \times \eta_5$. Equation 11 can be expressed as follows:

$$E_T = \eta \sum_{t=0}^{N} \sum_{k=t\cdot n}^{(t+1)n-1} \left(a_0 + a_1 \cos\left(\omega k + \theta\right)\right) e^{-\alpha \cdot (k-t\cdot n)} \quad (12)$$

$$E_T = \eta \sum_{t=0}^{N} \sum_{k=t\cdot n}^{(t+1)n-1} \left(a_0 + a_1 \cos\left(\omega k + \theta\right)\right) \times \sum_{t=0}^{N} \sum_{k=t\cdot n}^{(t+1)n-1} e^{-\alpha \cdot (k-t\cdot n)} \quad (13)$$

The series of (13) can be expressed by:

$$E_T = \eta \sum_{k=0}^{T-1} \left(a_0 + a_1 \cos\left(\omega k + \theta\right)\right) \frac{T}{n} \sum_{k=0}^{n-1} e^{-\alpha \cdot k} \quad (14)$$

The previous series are given by

$$E_T = \frac{\eta T}{n} \left(\frac{e^{-\alpha \cdot n} - 1}{e^{-\alpha} - 1}\right) \times \left(T \cdot a_0 + \frac{a_1}{2} \left(1 + \frac{\sin\left(\omega \frac{2T-1}{2}\right)}{\sin\left(\frac{\omega}{2}\right)}\right)\right) \quad (15)$$

The cleanning cost and energy revenue are given by (16) and (17), respectively.

$$C_c = u_c \cdot \frac{T}{n} \quad (16)$$
$$E_c = E_T \cdot e_c \quad (17)$$

Hence, the optimal cleaning strategy is:

$$0 = \frac{d}{dn} \left(\frac{T}{n} \left(\frac{e^{-\alpha \cdot n} - 1}{e^{-\alpha} - 1}\right) E_c - u_c \cdot \frac{T}{n}\right) \quad (18)$$

Finally, the solution of (18) is expressed by:

$$0 = e^{\alpha \cdot n} \cdot \left(e^{\alpha} \cdot (u_c - E_c) - u_c\right) + (n \cdot \alpha + 1) \cdot e^{n} \cdot E_c \quad (19)$$

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