Operational Planning for Cleaning Decentralized PV Solar Panels Considering Uncertain Dusty Air Condition

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MSc. Thesis

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A thesis submitted to Khalifa University of Science and Technology in accordance with the requirements of the degree of MSc. in Engineering Systems and Management in the department of Industrial and Systems Engineering.

Operational Planning for Cleaning Decentralized PV Solar Panels Considering Uncertain Dusty Air Condition

by

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A thesis submitted in partial fulfillment of the
requirements for the degree of

MSc. in Engineering Systems and Management

at

Khalifa University

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Abstract

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The performance of the PV system is affected by the actual weather condition; over time, dust accumulates on the panel surface, causing significant deterioration, blocking, or limiting solar irradiance, and reducing efficiency, especially in arid regions where rainfall is scarce. The amount of this accumulation depends on several factors, including the dust property in the area where the module is installed, wind velocity, humidity and rainfall, tilt angle and orientation, and the surface structure of the module.

Due to the expected growing demand for PV modules in the UAE, the most successful cleaning strategy should be developed to maintain high-performance systems. The research issue is how to make cleaning schedules in the face of the unpredictable dusty air. Three-year data for several meteorological parameters in the Abu Dhabi area was collected from various sources, including, particulate matter, wind speed, temperature, and solar irradiance. The data was then analyzed using multiple tools and statistical approaches, to determine the best cleaning schedule that guarantees the least possible cost. Preliminary results revealed that 45 days interval is the optimal cleaning schedule. A more accurate estimate was achieved when the simulation was employed, combining several values for the cleaning cost and electricity tariff, and examining various cleaning frequencies, from which the optimal cleaning interval was determined. 34 and 72 days were the optimal cleaning frequencies considering the electricity tariff for expats and UAE nationals respectively. These estimates were followed by a sensitivity analysis to identify the impact of changing these costs on the cleaning frequency.

Indexing Terms: PV, Panel efficiency, dust accumulation, cleaning, simulation optimization.

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Abubaker

Declaration and Copyright

Declaration

I declare that the work in this thesis was carried out in accordance with the regulations of Khalifa University of Science and Technology. The work is entirely my own except where indicated by special reference in the text. Any views expressed in the thesis are those of the author and in no way represent those of Khalifa University of Science and Technology. No part of the thesis has been presented to any other university for any degree.

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Chapter 1. Introduction

Solar energy is the thermal or electrical energy generated by converting the energy coming from the sun, SEIA (2022), it is an essential source of renewable energy, the cleanest and the most abundant one. And yet, according to IRENA (2021), a report published by the International Renewable Energy Agency, it only represents less than 3% of the global electric power generation, with around 700 thousand MW.

Nevertheless, in recent years, solar energy has gained public attention and attracted researchers in a variety of fields, and solar systems are now widely adopted in the global energy markets. They are improving in terms of both technology and economic viability. This advancement can be credited to the ongoing research and development, which is aimed at ensuring the reliability of renewable energy systems; there have been significant scientific efforts to improve these systems' effectiveness and make them cheaper than other systems; to meet the growing demand for clean energy.

Solar generation highly depends on the amount of irradiance coming from the sun. That is why the majority of the solar power farms are located in arid regions, with high levels of irradiance. However, a great portion of this irradiance gets reflected and scattered, taking into account that the absorbed portion is not completely converted into electrical energy, because the efficiency of today's commercial modules does not exceed 25%, Clean Energy Review (2022).

Furthermore, in arid regions, there are significant airborne dust and sand that accumulate on top of the solar panel surface, which can significantly reduce the output power by limiting the amount of sunlight reaching the panel or completely blocking it. This issue is widely known as soiling, the accumulation of dust, dirt, leaves, and bird droppings on PV modules, Research Gate (2022). Many factors contribute to this issue, especially the environmental condition in the area where the modules are mounted.

1.1 Affecting parameters

The weather has a major impact on soiling, in terms of both particle deposition and removal. The airborne dust is the most dominant factor, followed by the wind speed, which can both bring the dust onto the panels as well as remove it. These parameters affect the amount of dust deposited on the surface that serves as shading, blocking, or limiting the sun's irradiance, and

thus, reducing the amount of power generated from the panel. Figure 1 illustrates the various affecting parameters, including airborne dust, wind speed, humidity, temperature, rainfall, and scheduled cleaning. The last one is the only controllable factor, and cleaning can restore full performance when done properly.

The chart also depicts the impact of cleaning intervals on the amount of accumulated dust. More frequent cleaning effectively reduces energy losses. However, it incurs a cost. Thus, it is critical operational decision to figure out the optimal cleaning frequency, with which the total cost of energy loss and cleaning is the minimum.

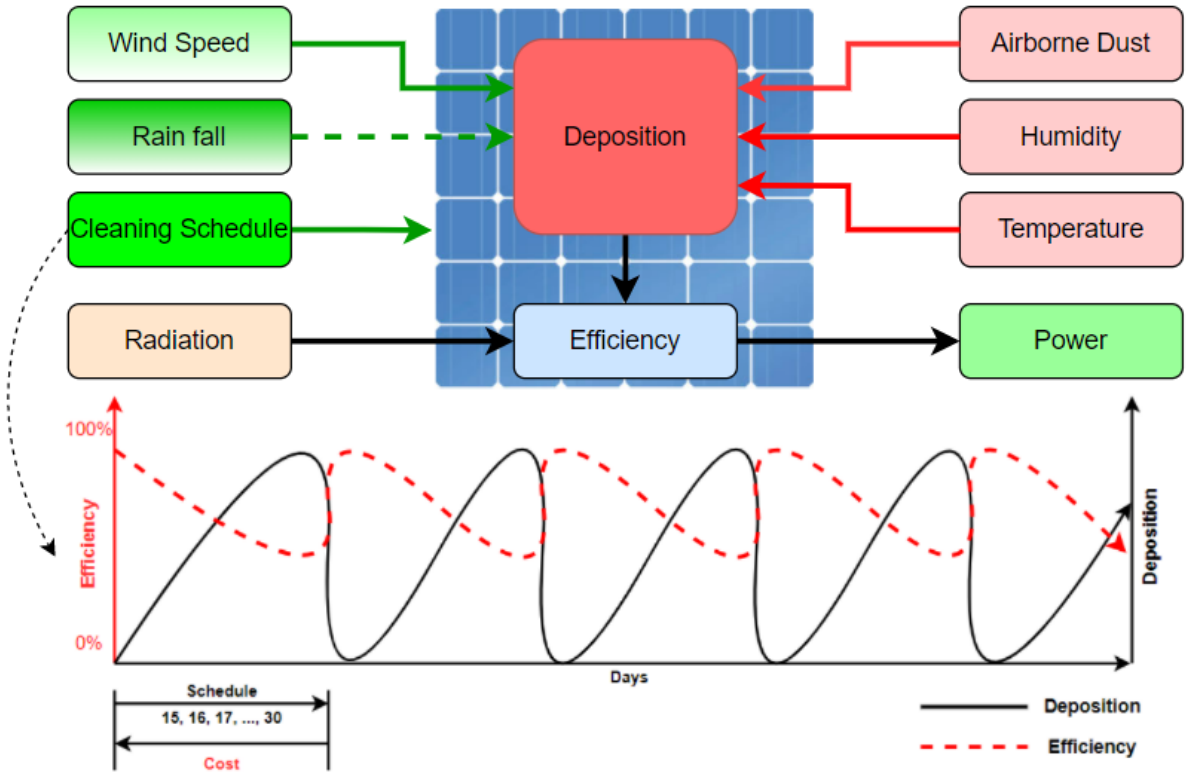

Figure 1: Dust deposition affecting parameters

1.2 Problem statement

Figure 2 illustrates the problem of this research. As the frequency of cleaning decreases (i.e., cleaning interval increases), the total cleaning cost decreases, and more dust accumulates on the module. Such accumulated dust will lower the efficiency of the PV system; and, consequently, reduce the generated power, which will impact the overall cost of the photovoltaic module (i.e., the summation of cleaning and lost energy costs). The blue dotted line shows this.

The green line represents the uncertainty related to weather factors, which randomly affect dust accumulation. Hence, early cleaning or postponing the cleaning action affect the PV panel efficiency.

Nevertheless, there might be a better option. Considering the cleaning cost and electricity tariff, it could be cheaper to conduct moderate cleaning, and purchase the required amount of electricity from the grid. The lowest point in the total cost curve can be achieved if the cleaning is performed every 'X' days, which is the optimal cleaning interval.

Therefore, it is an optimization problem in general, trying to trade-off between the cost derived from frequent cleaning and the cost of compensating for the lost energy.

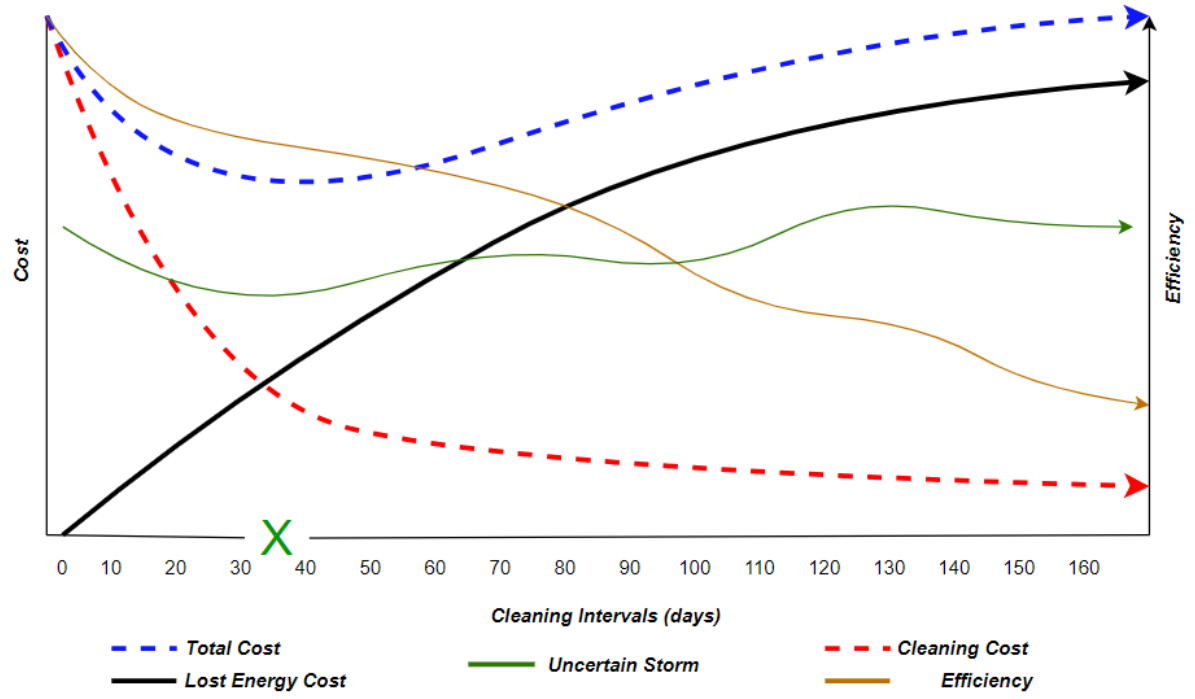

Figure 2: Problem statement

1.3 Research objectives

In order to address the aforementioned issues, this research has several objectives as follows:

- To model uncertain weather conditions such as airborne dust and wind speed and relate them to dust accumulation.
- To model the impact of soiling and weather conditions on the efficiency of a PV module
- To determine the optimal cleaning frequency for solar modules installed in Abu Dhabi
- To investigate the impact of cleaning cost and electricity tariff on optimal cleaning frequency

1.4 Research questions

This study will address the following questions:

- What is the effect of soiling on the efficiency of PV solar modules?
- How can weather data be used to quantify soiling and thus efficiency degradation?
- How much energy would be lost, and how much would that cost if cleaning is not considered for a certain period?
- What is the optimal cleaning frequency that results in the minimum total cost?

The rest of the paper is organized as follows. A comprehensive literature review for the related topics is presented in the second section of this study, which is followed by section 3, which provides a detailed description of the methodology used to conduct this research. After that, section 4 analyzes the experiment results. The outcomes and findings of this research are discussed and summarized in section 5. Finally, section 6 provides conclusions, discussing the limitations and the potential future improvements.

Chapter 2. Literature Review

Many studies have been reviewed, highlighting the major investigated issues and the leading solutions and mitigation approaches. The publications focus on a variety of topics, dust accumulation and its influence on PV modules, cleaning methods and mitigation strategies, simulation and modeling for efficiency degradation due to soiling, and financial implications and cost derivation of solar systems are among the subjects covered in the articles. Then, related studies were compared and classified based on the above-mentioned categories.

2.1 Effect on PV output

Among the previous research, the impact of dust deposition on the solar-panel modules has been a major area of concern. A very comprehensive review of the affecting parameters has been introduced by Said et al. (2018), covering the effect of wind velocity, wind direction, the surface structure of the module, characteristics of dust particles, temperature, PV manufacturing materials, coating materials and types of glass covers, humidity, tilt angle, and orientation, in addition, the author discussed current and future mitigation methods.

Most studies monitored and reported the decrease in the performance of PV modules as a function of dust accumulation. Gholami et al. (2021) reviewed different parameters that affected the deposition and highlighted several challenges that need further investigation to accomplish better utilization of PV modules. Zaihidee et al. (2016) as well, reviewed and summarized the impact of dust on the efficiency of the solar panel, demonstrating that efficiency degradation is linear with the dust density. Similarly, the efforts of Hachicha et al. (2019) revealed a linear relationship between the normalized power and the dust density with a drop of 1.7% per g/m^2 when the authors did indoor and outdoor experiments in Sharjah, UAE. They also revealed that tilt angle has a substantial impact on the deposition. Dabou et al. (2016) evaluated the performance of grid-connected PV modules exposed to several weather conditions in southern Algeria; they found out that changes in solar irradiance are caused by variations of dust storms that affect the stability of the PV system. Nonetheless, performing experiments indoors with artificial weather conditions differs from performing them outdoor in the natural environment, which was investigated by Gaglia et al. (2017). They conducted an outdoor experiment and used multiple correlation techniques to estimate actual PV output, which was around 18% lower than that under laboratory test conditions.

Furthermore, Benatiallah et al. (2012) developed three equations to calculate power, current, and efficiency as a function of the accumulated amount of dust on the PV module. Later, the efficiency formula was utilized in this research. Another important study by Figgis et al. (2018), attempted to quantify the amount of dust that deposits every day on the module surface. They used stepwise regression analysis and derived very distinctive formulas to calculate daily deposition and resultant accumulation considering several meteorological metrics. They found out that the wind speed is the dominant factor affecting the deposition more than particulate matter and humidity, especially when the speed exceeds 3 m / s, at which the panel becomes cleaner. And undoubtfully, the module becomes fully clean if there is rainfall that exceeds 3 mm per day, according to Javed et al. (2020). The recorded weather factors and PV module power levels over six years and reported that there was negative soiling in 75% of the research duration, while resuspension happened in only 25%.

On the other hand, some researchers attempted to quantify the loss in the performance of the panel if it is left dirty for a certain period. Adinoyi and Said (2013), for example, indicated that when solar PV modules are left unclean for more than six months, their output power decreases by 50%. Ramli et al. (2016) in Saudi Arabia also monitored the humidity by developing a measurement system using a simple rule-based model. The results showed that after two weeks' exposure in the dry season, the PV output power decreased by 10.8%. At the same time, Menoufi et al. (2017) analyzed the composition and distribution of the dust on the surface of PV panels in the East Bank of the Nile region, by introducing a new concept of the PV Soiling Index. Their results showed a uniform distribution and the overall power capacity dropped by more than half. Similarly, Abdelsalam et al. (2021) in Sharjah, UAE studied the nature of particles and their effect on power reduction, which was 8.46% after 41 days.

The area in which the panel is mounted, has a substantial impact on the soiling issue. The results found in one area cannot be generalized to others. That was why Boyle et al. (2015) approximated the results from two different places. They measured dust accumulation rates in two sites in the USA, then derived a regression model for their collected data. They observed that the accumulation rate was 50 $mg/m^2/day$, and the transmission reduction was 11%. Changing the place requires changing the module’s tilt angle. Tamizhmani et al. (2017) analyzed the data of five soiling stations in the USA at ten different tilt angles. They indicated that the annual soiling loss highly depended on the tilt angle.

Thangaraj and Velury (2016) examined the effect of soiling on four different technologies installed on a single rooftop for a month. Despite the short duration of its experiments, the study came out with quantified data on PV losses regarding the four technologies with a 22% reduction being the highest. Similarly, (in Al Ain, UAE), Shah et al. (2020) measured the drop in irradiance intensity and power output for four selected cleaning frequencies. The study revealed that for three months schedule, the output power drops by 13%, and only 4% when 15-day cleaning interval was employed. The effect of a longer duration has been addressed by Kazem and Chaichan (2019), who did their experiment in The Sultanate of Oman, which is close to Abu Dhabi. Their findings indicate how dust accumulation, dominated by particulate matter, varies over the year. They also addressed how rain reduces this accumulation.

The region also plays a big role in the characteristics of dust particles and the required tilt angle. The effect of these two factors has been investigated by Lu and Zhao (2018). They reported that the accumulation increases with the more horizontal mounting of the modules, in addition, they developed an empirical model to estimate the reduction in output considering dust deposition and tilt angle.

2.2 Modeling and Simulation

The advancement of modeling has made a substantial contribution to soiling investigations. Wang et al. (2017) developed two models that can be applied to evaluate and forecast the influences of dust deposition on the transmittance of PV modules. Likewise, Darwish et al. (2018) found a correlation between dust accumulation and PV current, voltage, power, and efficiency. They developed polynomials of the seventh degree and validated the models proposed by Benatiallah et al. (2012). They found that their models give accurate results and can be used for all dust deposition values, unlike Benatiallah's models which resulted in invalid values when applied to accumulation levels higher than 10 g/m^2. However, these formulas have been used in the current research, and they gave good results.

Moreover, You et al. (2018) developed a framework that uses data for humidity, tilt angle, and precipitation, to estimate the economic impact (net present value) of solar system soiling and, consequently, determine the optimal cleaning frequency. The framework was used in seven cities around the world, including Doha, for which the efficiency losses reached 80%

over 140 days. Interestingly, they found that changing the tilt angle by ±10 degrees results in only a 0.01% decrease in the efficiency.

Further studies combined experimental analysis with simulation and modeling. When Rao et al. (2014) combined indoor simulations and outdoor experiments and found that the deposition does not significantly alter the PV system's open-circuit voltage. However, it affects the short circuit current by 30-40%. Likewise, Bergin et al. (2017) integrated field measurements and modeling and assessed the impact of particulate matter related to fossil fuel combustion on solar power generation; their results show that about 11 GW of annual power reduction was recorded in China, 17% with respect to the ~ 65 GW installed solar energy capacity at that time.

A new unit to estimate the accumulated amount of dust was introduced by Shaaban et al. (2020), who developed a regression tree model that is equipped with the power of machine learning, making use of their experimental records of irradiance, temperature, and the power out of PV module. The estimate will help decide on cleaning actions only when required.

Also, Gherboudj and Ghedira (2016) proposed innovative maps to estimate the UAE land capability for PV and CSP power plants, they integrated solar irradiance maps with the weather condition and the topography of the land, and their findings revealed that PV plants are more appropriate for UAE than CPV plants.

2.3 Mitigation Techniques

Nowadays, research is becoming more directed toward the mitigation of dust problems, from the PV module's structural design that significantly affects the amount of deposition to cleaning techniques development that can fully restore the panel efficiency. Many researchers assessed the effect of soiling on solar generation and derived mathematical formulas for the optimal cleaning interval regarding specific areas. Abu-Naser (2017) developed a formula for the optimal cleaning periods. However, the work was based on the assumption that the accumulation linearly increases with time. Similarly, Jones et al. (2016) derived a general expression for the optimal cleaning intervals. They applied it to modules over a year in Central Saudi Arabia, and the results showed that optimal cleaning costs are smaller than typical operation and maintenance costs. Bunyan et al. (2016) also experimentally investigated the proper scheduling for cleaning PV modules in Kuwait; their results indicated a significant degradation in April, May, and October, in which the experimental panels needed weekly

cleaning to maintain efficiency losses of less than 15%, and for the rest months, the 30-day interval was appropriate.

As for the cleaning methods, advanced materials, techniques, and technologies have been developed for more effective cleaning. Saravanan and Darvekar (2018) comprehensively discussed various cleaning methods to mitigate dust deposition and increase the efficiency of electricity generated and the solar panel's durability and found out that Electrostatic Cleaning is the best option. Also, Al Shehri et al. (2016) reviewed different cleaning methods and addressed the dry-cleaning technique using a robotic system. Abhilash and Panchal (2016) also designed a microcontroller-based self-cleaning and tracking robot, equipped with two algorithms. And not far from robotics, Mohsin et al. (2018) implemented an intelligent automatic cooling and cleaning system that is activated based on power output; their system increased the energy by 8.7% compared to the ordinary panel. Jamil et al. (2017) discussed soiling types, presented some mitigation techniques, and compared them functionally and economically. The found that the most effective one is labor-based. However, it is costly.

A very interesting cleaning method was introduced by Mazumder et al. (2017); the results they came up with showed that 95% of the initial power could be restored when using electrodynamic screen film technology as dry cleaning for the panel. Their study also showed that the operation does not require too much power, only 0.2 Wh/m^2/cycle.

2.4 Economic Effect

Finally, the costs of maintaining the reliability of PV modules, prevention methods, cleaning, and the expenses of energy lost/gained under environmental parameters have been investigated. A work done by Zhao et al. (2019) evaluated the soiling cost of PV power plants in China to be $0.0161-0.0222 million per MW, which can be reduced by 36.5-50.3%, if their proposed optimal cleaning interval is applied. Based on a model developed after experimental investigation, they suggested a cleaning frequency of 10 and 23 days when using dry and wet cleaning methods respectively. Also, Alhammami and An (2021) discussed a policy to make rooftop residential solar panels attractive for people living in Abu Dhabi. Furthermore, Bazilian et al. (2013) economically reanalyzed and compared PV energy to other power generation options and added some level of transparency. Similarly, Lamont (2013) presented a cost comparison study for PV cleaning systems in remote sites in the UAE by breaking down the cost components of three cleaning methods.

On the other hand, Tanesab et al. (2016) indicated that the total cost of production losses caused by dust was lower than the total cost of cleaning.

Most of the reviewed works were done in laboratories or small-scale outdoor experiments that do not cover the whole year. In this research, a systematic method for calculating the optimal cleaning frequency has been introduced, which uses various meteorological data for the area where the PV module is mounted and utilizes some formulas from the reviewed literature. This is the first research to leverage the particulate matter data recorded by NASA for cleaning schedule optimization, and the first to use the simulation to mimic the environmental parameters while addressing the uncertainty issue regarding the weather condition. The study is focused on the Abu Dhabi area, and all the data gathered is held within the city's boundaries.

Quantifying the degradation in efficiency over a certain duration is very crucial for this study. Therefore, this particulate information has been further looked into, Table 1 provides varying values for this decline (Performance reduction, PR%) across different sites and time frames.

Table 1: Degradation in efficiency over time in different locations

PR %	Duration	Location	Reference
13	3 months	UAE, Al Ain	Shah et al. (2020)
12.7	5 months	UAE, Sharjah	Hachicha et al. (2019)
8.46	41 days	UAE, Sharjah	Abdelsalam et al. (2021)
20	1 month	UAE, Masdar	Mokri et al. (2013)
30	2 months	UAE, Masdar	Mokri et al. (2013)
40	2 months	UAE, Masdar	Mokri et al. (2013)
80	140 days	Qatar	You et al. (2018)
43	6 months	Qatar	Zeedan et al. (2021)
10	100 days	Qatar	Touati et al. (2012)
1	1 day	Qatar	Martinez-Plaza et al. (2015)
50	6 months	KSA	Adinoyi and Said (2013)
40	10 months	KSA	Walwil et al. (2017)
20	45 days	KSA	Said and Walwil (2014)
17	6 weeks	KSA	Said et al. (2015)
10.8	2 weeks	KSA	Ramli et al. (2016)
16.76	5 days	Yaman	Hadwan and Alkholidi (2018)
11	5 weeks	USA, Colorado	Boyle et al. (2015)

Chapter 3. Methodology

This section outlines the methodological steps followed in conducting this research. Figure 3 depicts these steps. They Start with gathering the data required for the study from reliable and reputable sources. Then, basic processing is performed on the collected data, followed by the calculations of several metrics that are necessary to drive the total cost, and consequently, determine the best cleaning frequency. Then, simulation and optimization are utilized to improve the results by examining possible cases. Finally, analyses for the results acquired is provided.

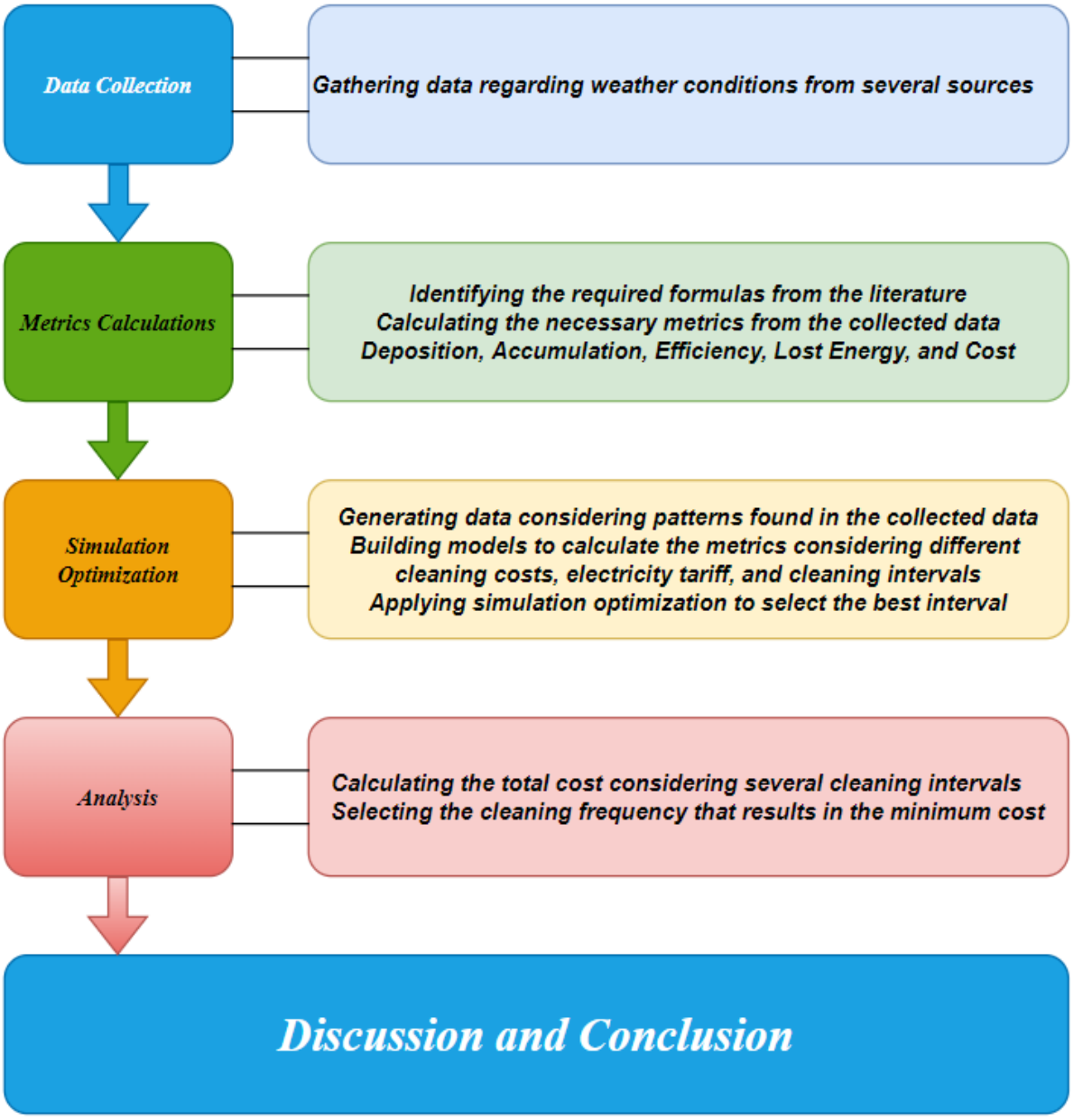

Figure 3: Research Methodology Flowchart

3.1 Data Collection

The data was gathered from a variety of sources that monitor changes in the atmosphere and the earth's crust and provide meteorological services. The sources include:

- **W**orld **M**eteorology **O**rganization, **S**and and **D**ust **S**torm **W**arning **A**dvisory and **A**ssessment **S**ystem, WMO (2020)
- **N**ational **C**enter of **M**eteorology, UAE, NCM (2021)
- Abu Dhabi Electricity Distribution Company, ADDC (2022)
- Bayanat, the official data portal of the UAE government, Bayanat (2021)
- Meteostat website, Meteostat (2022)
- Wunderground website, Wunder (2017)

Four parameters were gathered, particulate matter, irradiance, wind speed, and temperature. Three years of data for 2018, 2019, and 2020 in Abu Dhabi have been collected. The daily average was utilized for temperature, wind speed, and irradiance. Particulate matter was captured at 12:00 PM GMT.

There were a few missing data points for all the attributes. Average values were utilized to substitute the missing data points. In addition, the data for the 29th day of February in 2020 was waived because this month only has 28 days in 2018 and 2019.

The data for the particulate matter attribute was in "NetCDF" format (Network Common Data Form), a file format that supports the creation, access, sharing, and storing of multi-dimensional scientific data. Such data were converted to a CSV format, using the Weather and Climate Toolkit software distributed by the National Centers for Environmental Information that the National Oceanic and Atmospheric Administration own. The tool also allows the visualization, mapping, animation, and basic filtering of the weather data, making it easier to select data for the Abu Dhabi area exclusively.

3.2 Metrics Calculations

To be able to determine the optimal cleaning frequency, several parameters need to be computed first. Figure 4 shows these metrics and the sequence of calculating them. The daily deposition is calculated first, and its value is used to calculate the accumulation over certain period, which is used to calculate the efficiency on which the energy generated from the module depends.

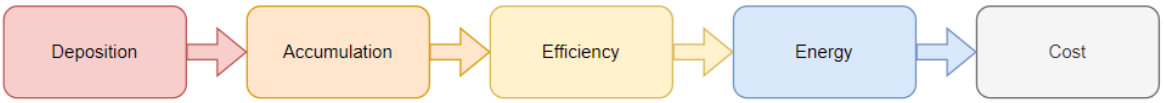

Figure 4: Metrics calculation sequence

3.2.1 Daily Deposition

Firstly, the daily deposition was computed using the accumulation formula proposed by Figgis et al. (2018). The formula employs both the wind speed and the particulate matter predictors to estimate the daily deposition in $\mu gm/m^2$ per minute. However, wind speed has the greatest influence on the overall accumulation rate. The formula is illustrated as follows:

$$Dep = 10.6 - 4.99WS + 247PM - 73.4WS.PM - 14.9\Delta WS \qquad (1)$$

Where Dep is the daily deposition, WS stands for wind speed in m/s, and PM stands for particulate matter in g/m^2. The last term $(-14.9\Delta WS)$ was ignored since it is too small. In addition, there was no data for the wind speed in the previous hour from which the deviation in WS is calculated.

3.2.2 Accumulation

As for the accumulation, the daily deposition calculated by Equation (1) is summed up over a certain period to compute the accumulation, Figgis et al. (2018) observed an apparent negative correlation between accumulation and wind speed; with the stronger wind, the dust accumulation rate decreases; When the wind speed exceeds 3m/s, the panel consistently becomes cleaner on average. However, this is not the case in the UAE, a region with high values of humidity. Therefore, in order for Equation (1) to be applied to the collected data; and for its output to be used in other equations, it needed some sort of modification that is explained in the following equations:

$$DDep = (10.6 - 4.99WS + 247PM - 73.4WS.PM - 14.9\Delta WS) * 0.00144 \qquad (2)$$

0.00144 is multiplied to convert the unit of Dep from $\mu gm/(m^2.min)$ to $gm/(m^2.day)$, so that the value can be used in the efficiency equation. $DDep$ here stands for the daily deposition. When Equation (2) returns a negative value, that would mean the high wind speed has caused a natural cleaning effect. However, dust will not be removed completely due to the high level of humidity in the region. Therefore, a new factor is proposed, the calibration factor (α), which is a ratio that indicates the amount of dust that is naturally removed by the wind.

$$DDep' = \begin{cases} DDep, & DDep \geq 0 \\ \alpha * DDep, & DDep < 0 \end{cases} \quad (3)$$

$DDep'$ stands for the modified daily deposition. If $DDep$ is negative, its effect will not be considered a hundred percent. Dust accumulation can be expressed as the sum of the accumulation in the previous day and today's deposition, as presented in Equation (4).

$$Acc(t) = Acc(t-1) + DDep' \quad (4)$$

Unless the module is intentionally cleaned by a labor, we cannot assume that the dust is completely removed from it; there would always be some residues. To reflect that assumption, β is introduced in Equation (5) to calculate the value of the modified accumulation $Acc(t)'$.

$$Acc(t)' = \begin{cases} Acc, & Acc \geq \beta \\ \beta, & Acc < \beta \end{cases} \quad (5)$$

To compute the value of the calibration factor, α in Equation (3), an Excel optimization solver was used (as described in Appendix C), leveraging the information mentioned in Table 1, specifically from Mokri et al. (2013).

3.2.3 Efficiency

Efficiency decreases as dust accumulate on the panel. It is computed using a formula developed by Darwish et al. (2018).

$$Efficiency = -0.0026 * Acc(t)'^3 + 0.032 * Acc(t)'^2 - 0.1369 * Acc(t)' + 0.192 \quad (6)$$

The accumulated amount of dust ($Acc(t)'$) in Equation (6) should be in g/m^2. The maximum efficiency of the panel is assumed to be 19.2%. Further detailed information regarding the specifications of the considered PV module is presented in Appendix A.

3.2.4 Lost Energy

Finally, the lost energy due to the decrease in the efficiency was calculated, utilizing Equation (7) proposed by Alhammami and An (2021), which calculates the expected amount of electrical energy generated from the PV panel, considering specific irradiance, temperature, and system efficiency.

$$E_{loss} = P * H * \big(1 - k(T - 25)\big) * (0.192 - Efficiency) \quad (7)$$

Where E_{loss} stands for energy loss in kWh, P for power in kW, H for irradiance in kWh/m^2, k for temperature coefficient which is assumed to be 0.0043, RENVU (2022).

3.2.5 Total Cost

The total cost is the summation of the total cleaning cost and the cost of lost energy. The first one is the multiplication of the number of cleanings required by the assumed cleaning cost taken from Shah et al. (2020) who assumed the cleaning cost in UAE to be 0.03 USD/m^2/cleaning cycle, similar to that one used in Saudi Arabia. In our case, considering a 1.96*0.992 m panel, the cost would be 0.0583 USD/cleaning cycle. The lost energy cost is computed by multiplying the energy lost by the electricity tariff, which was acquired from the Electricity Distribution Company in Abu Dhabi (0.073 USD for expats).

3.3 Excel calculations

The previous metrics were calculated for a variety of cleaning intervals, including 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 75, 90, 105, 120, 135, and 150 days. The daily lost energy considering each interval was summed together to calculate the cost of lost energy during a year.

Similarly, the cost of cleaning was calculated for each interval; by dividing the total number of days in a year (365) by the cleaning interval. The resultant value was multiplied by the assumed cleaning cost.

For each cleaning interval, the lost energy cost and the cleaning cost were summed together to identify the total cost of the panel. Then the total costs of intervals were compared together to select the interval with the least cost as the best cleaning schedule.

3.4 Simulation Optimization

Due to the high level of uncertainty in weather data, a discrete-event simulation- method has been utilized to mimic the target system by generating random variates of the four weather factors, such as airborne PM, wind speed, temperature, and radiation, based on the probability distribution fitted to the collected data. Then, the optimization model was embedded into the simulation model to minimize the total cost by accurately determining the best cleaning interval under the considered cost and tariff structure.

3.4.1 Simulation models

Two logics have been implemented, as illustrated in Figure 5, the first one (A) mimics the calculations done in the Excel, and the second one (B) considers resetting the cleaning interval whenever there is a windy day, utilizing the aforementioned outcomes of Figgis et al. (2018).

The Basic model (A) starts with generating weather factors before calculating the daily deposition, which was described in section 3.2. The model then checks whether this deposition is negative or not. If that is so, it will be multiplied by the calibration factor, and then added to the already existing amount of dust. If that is not the case, the deposition will be summed up with the existing dust directly. Then, the model checks if the current day is a cleaning day, by comparing the value of a counter with the adopted cleaning interval. The counter is increased by one every day and set to zero every time a cleaning action occurs. If they are equal to each

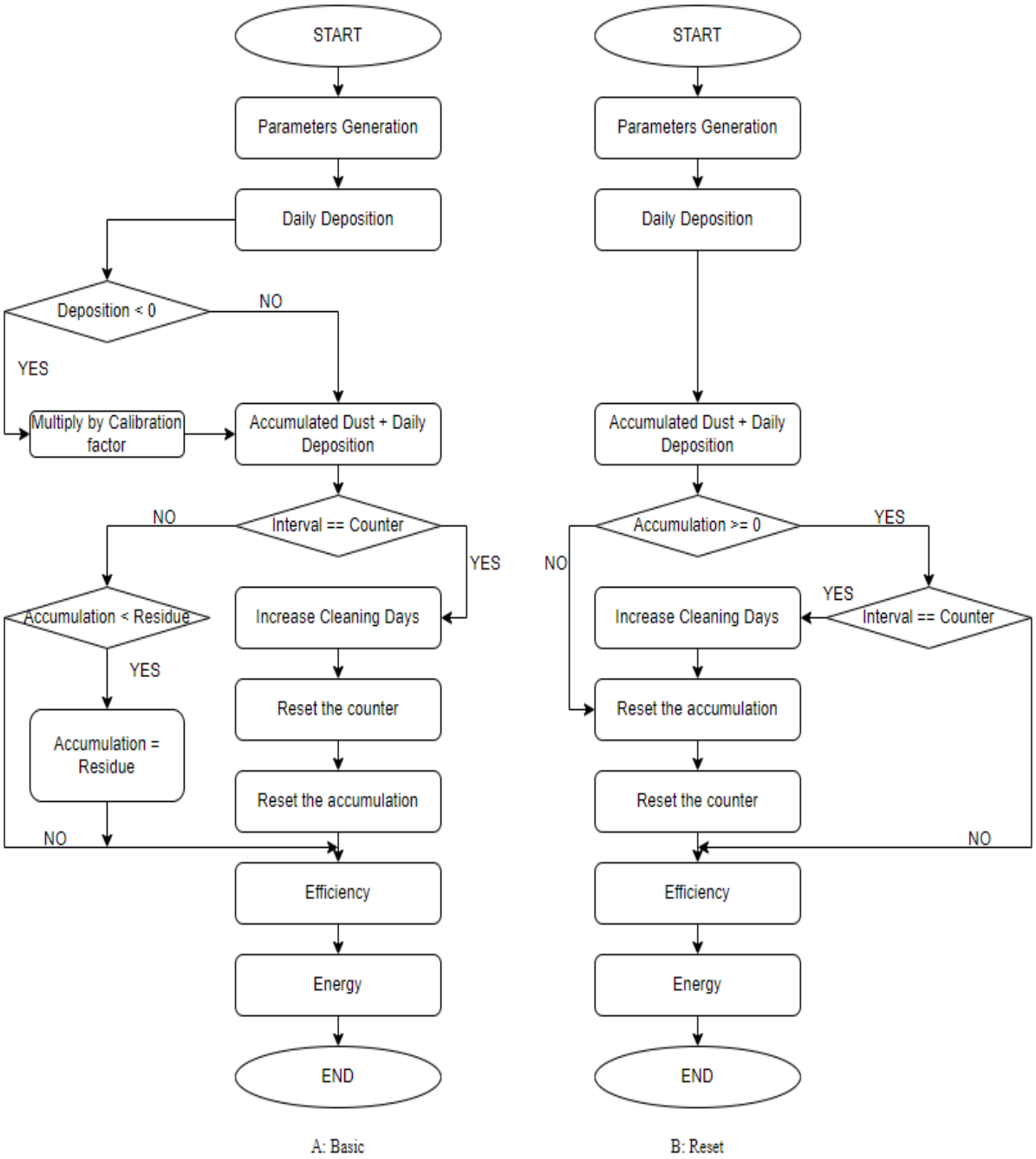

Figure 5: The simulation models

other, the number of cleanings will be increased, and the amount of the accumulated dust will be reset. If the current day is not a cleaning day (the counter value and the interval are not equal), the model will proceed to checking the accumulation value, if it is below the residue, the accumulation will be set to equal the residue, otherwise, the model continues to calculate the efficiency and finally, the lost energy.

The Reset model (B) is similar, except for the deposition and accumulation metrics. Whether the deposition value is positive or negative, it will be added to the accumulated dust. Then the model checks the value of the accumulation, if it is negative, it will consider that as a cleaning action, resulting in increasing the number of cleanings and resetting the counter and the accumulation. If it is positive, it will check if the counter equals the interval, to consider that as a cleaning day. And so on.

Figure 6 depicts the basic simulation model. The starting source generates values for the four parameters, then the entity that holds the data goes through numerous servers (which represent locations at which processes can be done), with one of the preceding calculations being performed in each one. This scenario was replicated tens of times to get more precise results.

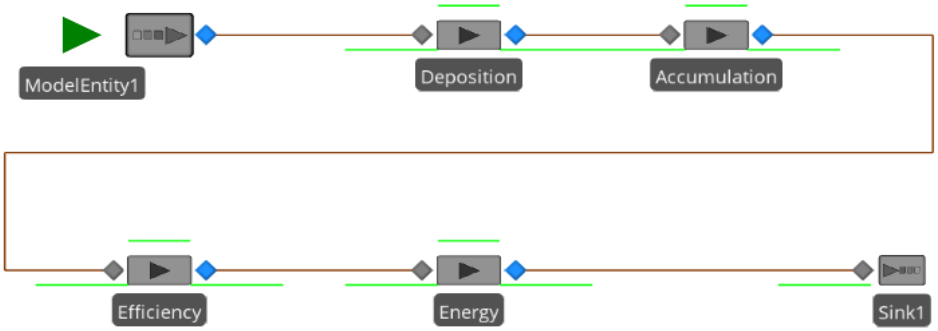

Figure 6: The basic simulation model

3.4.2 Optimization algorithms

Objective equation:

$$Minimize: Total\ cost = Cleaning\ cost + Lost\ energy\ cost \quad (8)$$

Subject to:

$$7 \leq Cleaning\ interval \leq 140 \quad (9)$$

$$Cleaning\ interval = Integer \quad (10)$$

The presented optimization model has been implemented using OptQuest, which is an add-in optimization module in Simio simulation software.

3.4.3 Experiment Design

To investigate the impact of the electricity rate and cleaning cost on the optimal cleaning cycle, 20 cases have been examined with two electricity rates, for expats (0.073 USD/kWh) and UAE nationals (0.018 USD/kWh), as well as five different cleaning cost (i.e., two higher and two lower values from the basic cleaning cost (0.0583 USD/panel/cycle)), using the Basic and Reset models. Table 2 describes and classifies these scenarios.

Table 2: Design of experiments for the Basic model

Policy	Electricity Tariff	S	Tariff (USD/kWh)	Cleaning Cost (USD/panel/cycle)
Basic	Expats	1	0.073	0.0183
		2	0.073	0.0383
		3	0.073	0.0583
		4	0.073	0.0783
		5	0.073	0.0983
	UAE Nationals	6	0.018	0.0183
		7	0.018	0.0383
		8	0.018	0.0583
		9	0.018	0.0783
		10	0.018	0.0983
Reset	Expats	11	0.073	0.0383
		12	0.073	0.0483
		13	0.073	0.0583
		14	0.073	0.0683
		15	0.073	0.0783
	UAE Nationals	16	0.018	0.0383
		17	0.018	0.0483
		18	0.018	0.0583
		19	0.018	0.0683
		20	0.018	0.0783

3.4.4 Simulation configuration

The duration of the simulation run is set to be 20 years (7300 days) (as per the assumed lifespan of the module), with a five-day initial warm-up period. Throughout all calculations, a 95% confidence level was used and a 0.1 USD indifference zone (The smallest meaningful difference that is used for defining the best.

Moreover, most scenarios were replicated more than 60 times.

Chapter 4. Results and Analysis

This section presents a statistical analysis of the data acquired from data sources. The second part shows the result obtained from manual calculations performed in Excel, and the last part describes and analyzes the results of the simulation experiments.

4.1 Descriptive analysis

A total of 3285 data points were collected for temperature, wind speed, and radiation, 1095 for each, and 730 data points for the particulate matter. A plot for the temperature collected in three years is presented in Figure 7-A (Temperature). The chart shows some variations in values over the three years, with the most noticeable changes occurring in January, February, and March. Minor changes were observed in August, October, November, and December, indicating a more stable temperature.

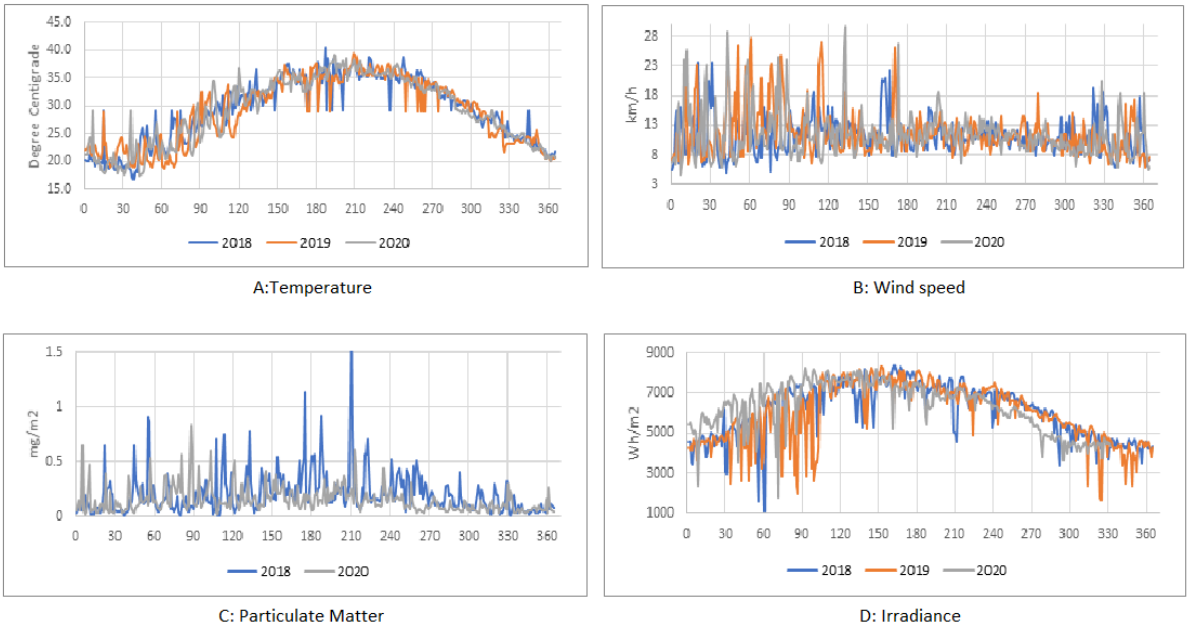

Figure 7: Three-year Data

The wind speed plot, on the other hand, showed high fluctuations, as can be seen in Figure 7-B (Wind speed), especially from January to June. Then the wind speed becomes relatively stable in July, August, and September, and again, the fluctuations appear in the last two months.

For the particulate matter, only two-year data were found from the data source WMO (2020) for the Abu Dhabi location (24.5 N, 54.375 E, latitude and longitude respectively). Thus, the data for 2018 was utilized for 2019 calculations.

Figure 7-C illustrates how dust fluctuates among the seasons in a hard-to-predict manner. The graph also shows the high uncertainty regarding the dust storms.

Finally, Figure 7-C shows the irradiance data, which was provided by the National Center of Meteorology, NCM (2021).

The average annual irradiance was 2213.4 kWh/m^2. The graph in Figure 7-C reflects a few fluctuations in the last days of February, April, May, and August; however, the general trajectory of the irradiance is that it increases in Summer and decreases in Winter with average highest and lowest values of 8330 and 1513.33 kWh respectively.

Statistical descriptive analysis for data was done using excel analytical tool. The results are summarized in Table 3.

Table 3: Statistical analysis of 2018 data

	Temperature	Wind speed	Particulate matter	Irradiance
Mean	29.09	11.35	0.17	6064.07
Standard Error	0.18	0.11	0.01	42.09
Median	29.50	10.8	0.13	6340
Mode	29.20	11.1	0.10	7260
Standard Dev.	5.93	3.58	0.16	1392.72
Sample Variance	35.11	12.8	0.03	1939665.84
Kurtosis	-1.27	4.17	24.90	-0.45
Skewness	-0.23	1.68	3.53	-0.51
Range	23.70	25	1.93	7260
Minimum	16.80	4.60	0.00	1120
Maximum	40.50	29.60	1.93	8380
Sum	31854.80	12424.00	127.67	6640160
Count	1095	1095	730	1095

4.2 Excel Calculations

After extracting the data in tabular format in excel, the equations mentioned in section 3 were applied, and the aforementioned intervals were tested, for a preliminary examination. Figure 8 illustrates the results of 2018 computations. As can be seen, cleaning cost decreases as the intervals increase. However, the accumulation increases causing a bigger loss in energy. As a result, cleaning cost is high with shorter intervals, and with longer ones, the cost of lost energy is high so that; the optimal interval could be found in the middle. The calculations resulted in 45 days as the optimal cleaning frequency. Similar results were obtained for 2019.

In contrast, the optimal interval was 55 days for 2020. Moreover, as the figure shows, the total cost curve has an unsmooth shape; due to a lack of smoothness in the lost energy cost curve, which is not consistently increasing while increasing the intervals; random events occur, causing unpredictable fluctuations in module efficiency, indicating uncertain outcomes. Therefore, simulation has been used to obtain more accurate and robust results.

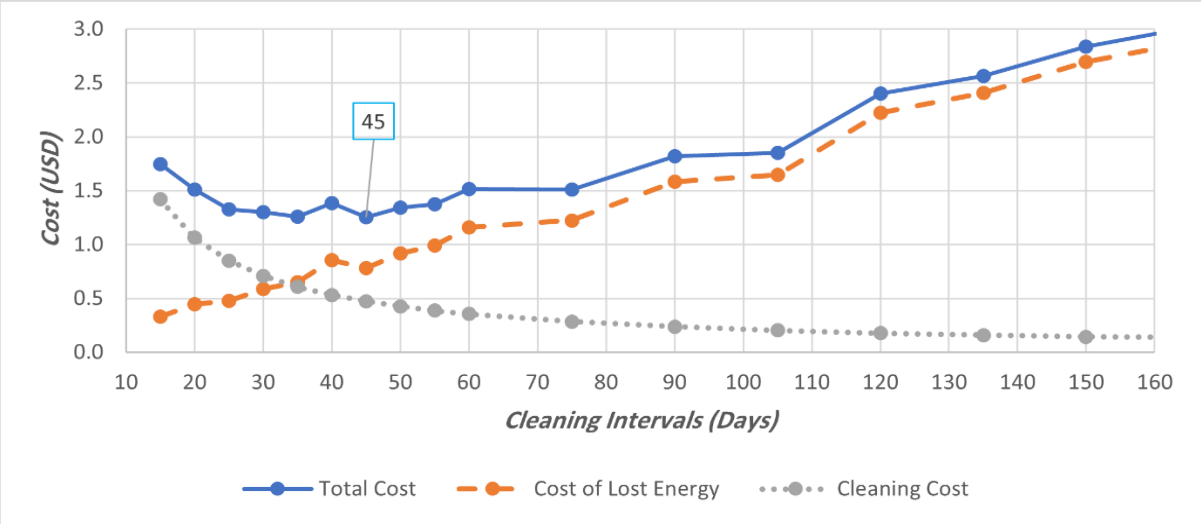

Figure 8: Excel calculation result for 2018

4.3 Simulation Results

The simulation begins with the generation of random data, followed by verification that these data match the collected one. Optimization experiments have been conducted using the two developed models. It is important to mention that all the analyses are based on one PV panel with a lifespan of 20 years, rated power of 330 W, and 19.2% efficiency.

4.3.1 Distributions of the collected data

To be able to generate data using the simulation tool, it was a must to know the distribution pattern of the collected data. A statistical tool (Stat::fit software by Geer Mountain (2021)) was used to determine the distribution, parameter by parameter and month by month to be able to generate more accurate and valid data. Table 4 summarizes these distributions which formats were altered to suit the simulation tool.

As the table shows, for one factor, there is no notable difference between neighboring months. However, there is a significant difference between months that are far apart, implying that fitting the distribution to relatively short-interval data (monthly); results in more representative distributions.

Table 4: Distributions of the collected three-year data

	Temperature	Wind Speed	Particulate Matter	Irradiance
1	Lognormal(17.0, 1.16, 0.559)	Lognormal(3.77, 1.82, 0.672)	Lognormal(1.56E-2, -2.78, 1.08)	Lognormal(-1.07E3, 9.62, 4.48E-2)
2	Lognormal(16.0, 1.57, 0.546)	Lognormal(4.05, 1.82, 0.657)	Lognormal(-1.05E-2, -2.0, 0.796)	Lognormal(-1.12E4, 9.69, 6.09E-2)
3	Triangular(18.0, 31.6, 22.2)	Lognormal(2.92, 2.24, 0.467)	Lognormal(-2.04E-2, -1.86, 0.684)	Lognormal(-1.92E4, 10.1, 5.4E-2)
4	Lognormal(13.2, 2.74, 0.178)	Lognormal(2.44, 2.2, 0.351)	Lognormal(-5.17E-2, -1.56, 0.568)	Lognormal(-1.86E4, 10.1, 5.47E-2)
5	Lognormal(-14.1, 3.84, 3.86E-2)	Lognormal(6.49, 1.47, 0.555)	Lognormal(-1.28E-3, -1.78, 0.648)	Normal(7.45E3, 651)
6	Normal(34.9, 1.64)	Lognormal(7.21, 1.25, 0.708)	Lognormal(9.11E-3, -1.64, 0.629)	Normal(7.72E3, 377)
7	Normal(36.1, 2.11)	Lognormal(4.9, 1.87, 0.309)	Lognormal(7.43E-2, -1.94, 0.811)	Normal(7.19E3, 614)
8	Lognormal(29.2, 1.92, 0.125)	Lognormal(-461, 6.16, 3.51E-3)	Lognormal(2.37E-2, -1.89, 0.946)	Normal(6.92E3, 520)
9	Normal(34.2, 1.72)	Lognormal(2.56, 2.12, 0.165)	Lognormal(7.96E-3, -1.97, 0.735)	Normal(6.64E3, 356)
10	Normal(30.8, 1.59)	Lognormal(6.25, 1.37, 0.374)	Lognormal(2.9E-2, -2.76, 0.718)	Normal(5.72E3, 471)
11	Triangular(21.3, 29.8, 27.9)	Lognormal(4.88, 1.58, 0.5)	Lognormal(-3.75E-3, -2.39, 0.694)	Lognormal(-1.85E4, 10.0, 2.92E-2)
12	Normal(22.8, 1.6)	Lognormal(4.89, 1.31, 0.695)	Lognormal(1.11E-2, -3.03, 0.581)	Lognormal(-1.02E4, 9.58, 2.91E-2)

4.3.2 Validation

In order to test the goodness of the fit of the distributions found for the weather data, data have been generated randomly using the distributions found. Then, an experiment was carried out using the same cleaning intervals, cleaning cost, and electricity tariff that were used in Excel. Figure 9 shows that the resulting curve from the simulation falls within other curves from excel, indicating the correct implementation of the computational logic on Simio.

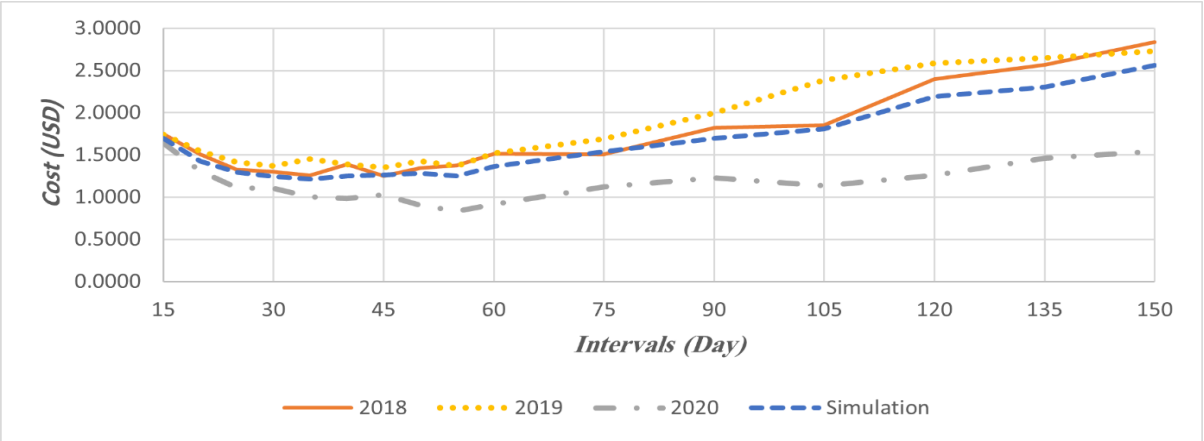

Figure 9: Simulation model validation

Moreover, the graphs generated from the simulation illustrated in Figure 10, showed a similar pattern to those in Figure 7.

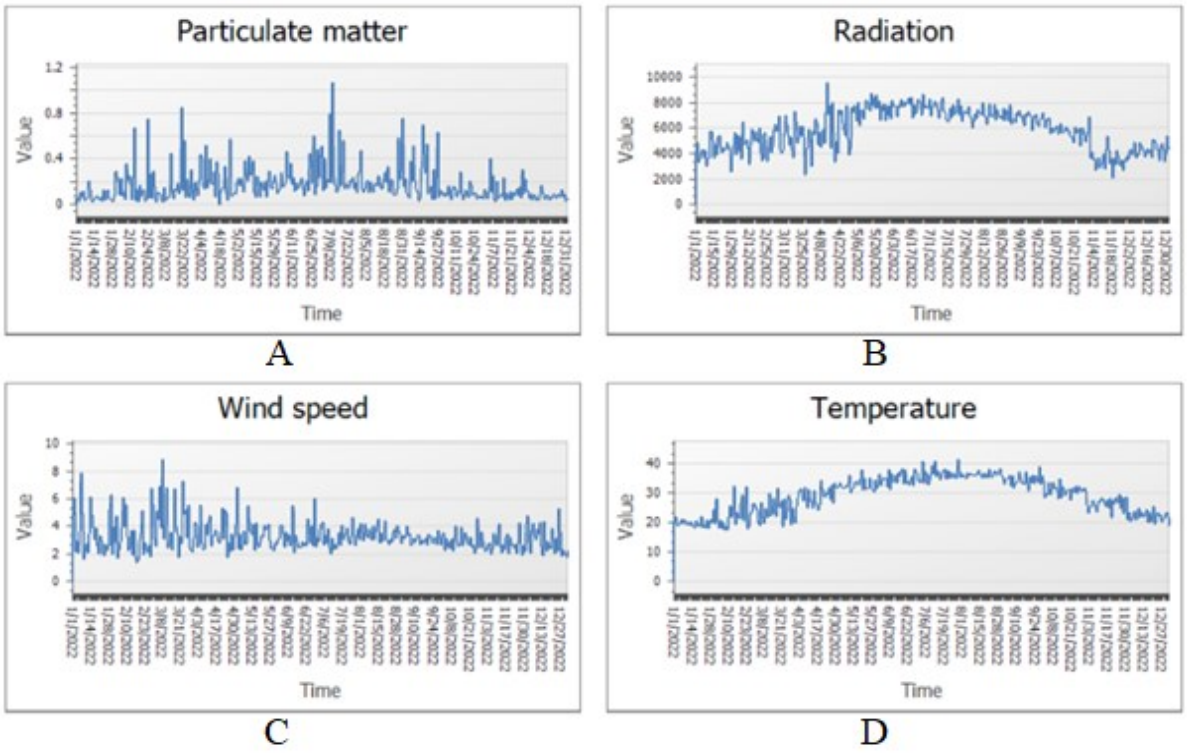

Figure 10: One-year generated data by Simio

4.3.3 Basic model

The results for the first ten scenarios of experiments designed and explained in Table 2 are shown in Table 5 and Table 6. The optimal cleaning interval for each scenario was determined, with the third scenario resulting in 34 days cleaning frequency considering the actual cleaning cost and expats' tariff. The efficiency column is the minimum efficiency observed while adopting the corresponding interval.

Table 5: Basic model result considering expats tariff (0.073$)

S	# Of cleaning	Cleaning cost (USD)	Lost Energy kWh	Lost energy cost (USD)	Total Cost (USD)	Optimal Interval	Efficiency (min) (%)
1	365	6.6795	103.35	7.54471	14.2242	20	71.92
2	251	9.613	143.61	10.48	20.10	29	67.57
3	214	12.48	165.37	12.07	24.55	34	64.63
4	178	13.94	195.65	14.28	28.22	41	61.99
5	155	15.2365	221.39	16.1616	31.3963	47	59.21

Figure 11 shows how optimal intervals in Table 5 were picked, the values for which the total cost was the lowest.

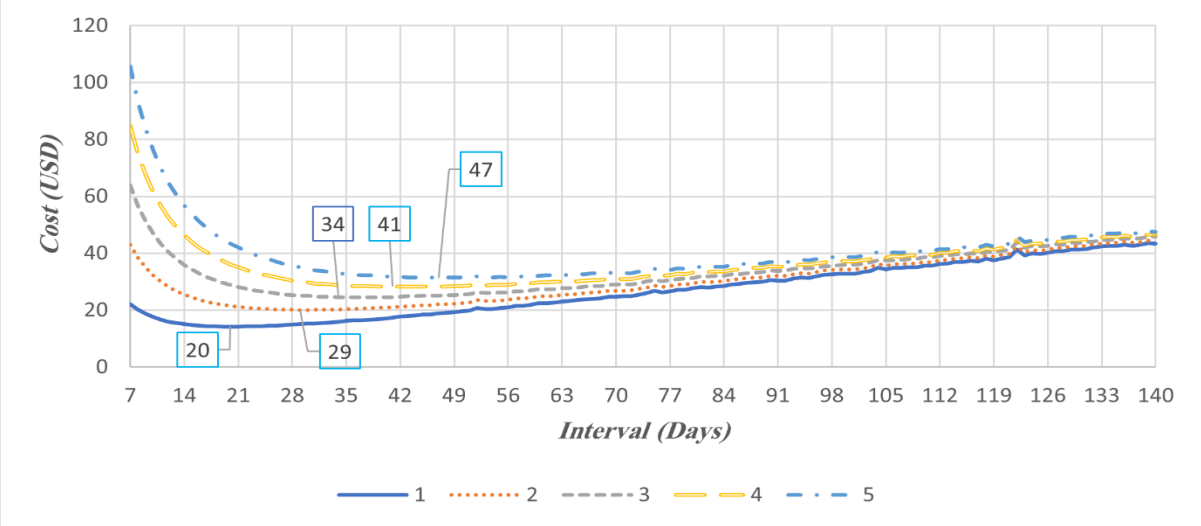

Figure 11: Optimal cleaning intervals for expats tariff and several cleaning cost with Basic model

Also, frequencies considering the UAE national's tariff were identified. They can be seen in Table 6. The intervals are much longer than those resulting from using the expats tariff, because the tariff in this case is much lower. Therefore, it might still be financially viable for a UAE national to delay the cleaning and buy energy from the grid to compensate for the lost energy. Moreover, Figure 12 shows the impact of changing the cleaning cost while using a small value for the electricity rate (UAE nationals' tariff).

Table 6: Basic model result considering UAE nationals tariff (0.018$)

S	# Of cleaning	Cleaning cost (USD)	Lost Energy kWh	Lost energy cost (USD)	Total Cost (USD)	Optimal Interval	Efficiency (min) (%)
6	178	3.2574	194.06	3.49313	6.75053	41	62.48
7	123	4.7109	271.1344	4.88042	9.59132	59	54.98
8	101	5.8883	320.1589	5.76286	11.6512	72	51.13
9	76	5.9508	414.8522	7.46734	13.4181	95	45.91
10	73	7.1759	431.35	7.76437	14.9403	99	44.48

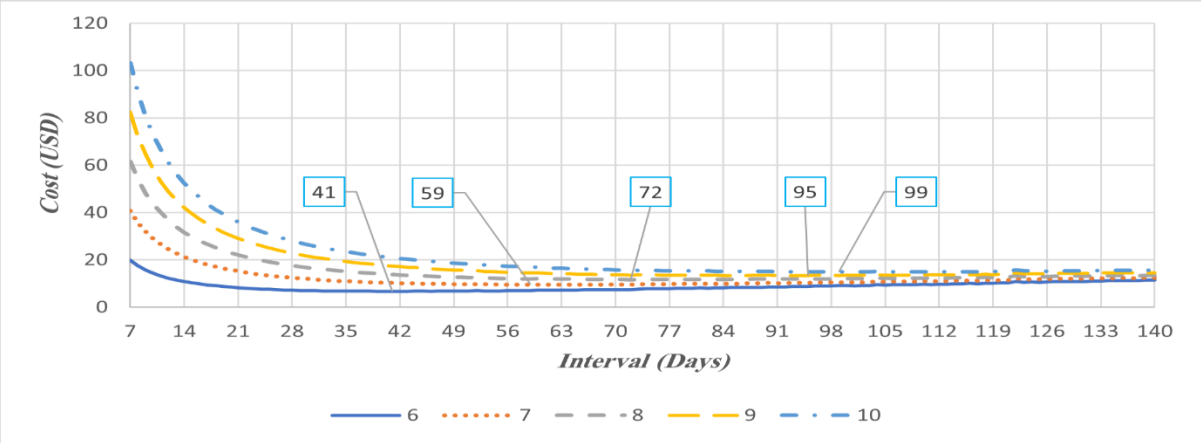

Figure 12: Optimal cleaning intervals for UAE nationals' tariff and several cleaning cost with the Basic model

Considering the third scenario, Figure 13 provides a plot for cleaning cost, lost energy cost, total cost, and the minimum efficiency when adopting each cleaning interval. Since we are performing tens of replications, these curves represent the average values for each interval. It is obvious that with rare cleaning, efficiency declines, resulting in more energy losses. In addition, the total cost considering short intervals is mostly built up of the cleaning cost, and for long intervals, it is mostly built up of wasted energy cost

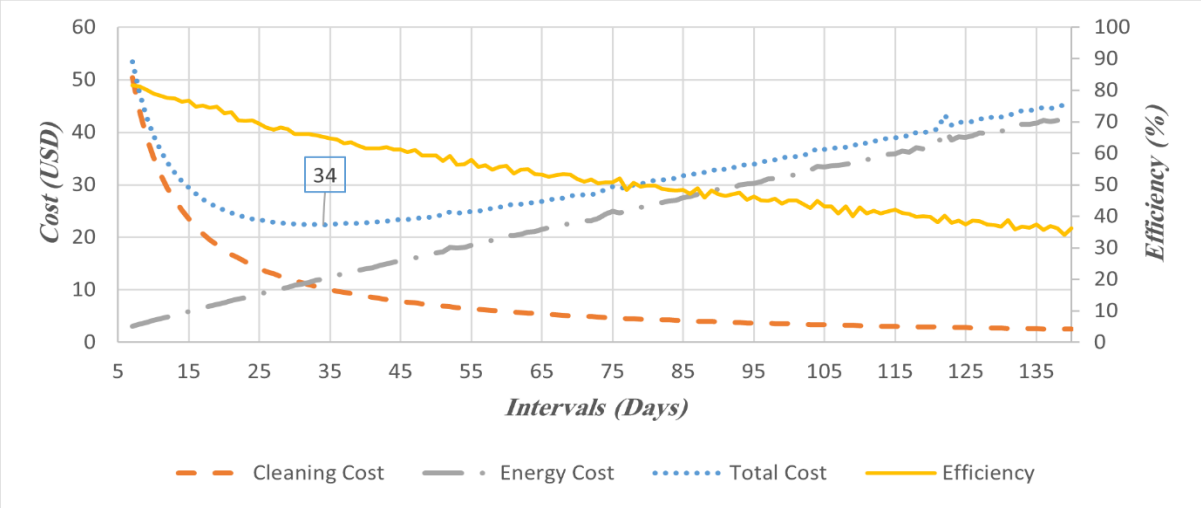

Figure 13: Simulation Output of the typical scenario (S3) for the Basic model

Figure 14, compares the results of the 3rd and 8th scenarios (with actual costs); when the optimal cleaning intervals found are applied. The cost of cleaning, lost energy, and total cost of scenario 3 (expats' tariff) are approximately two times higher than those of scenario 8 (UAE nationals' tariff).

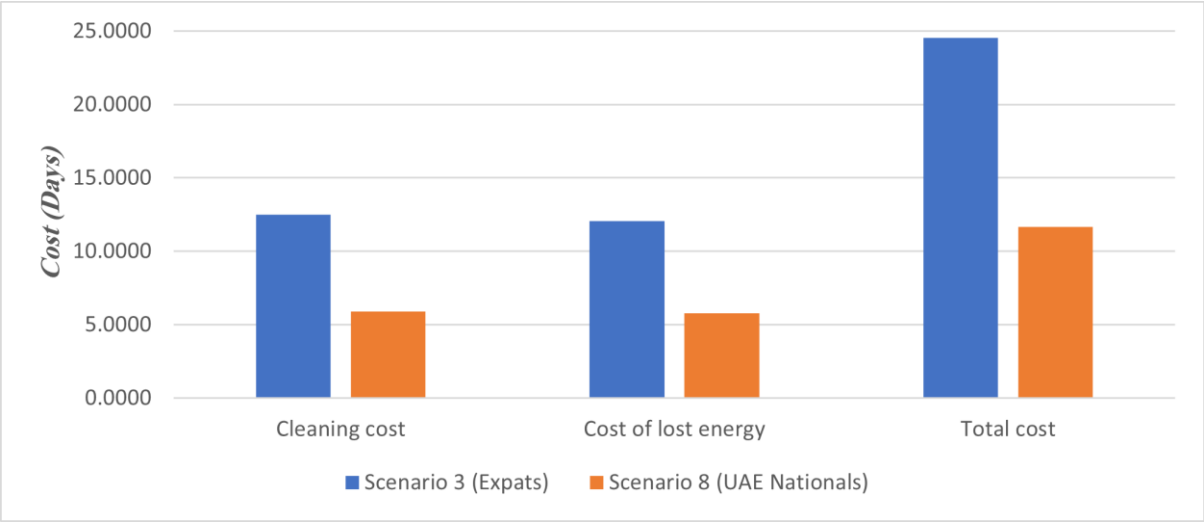

Figure 14: Cost comparison for the Basic model

On the other hand, as shown in Figure 15, the optimal cleaning interval, is considerably shorter for them; because they do not have the option of compensating for the lost energy from the grid at a lower price than UAE nationals have. Therefore, it is still beneficial for them to clean their modules at the prescribed frequency and restore their efficiency, rather than purchasing electricity from the grid at a significantly higher cost. For expats, more frequent cleaning keeps the efficiency at higher levels and the lost energy at lower levels than for UAE nationals.

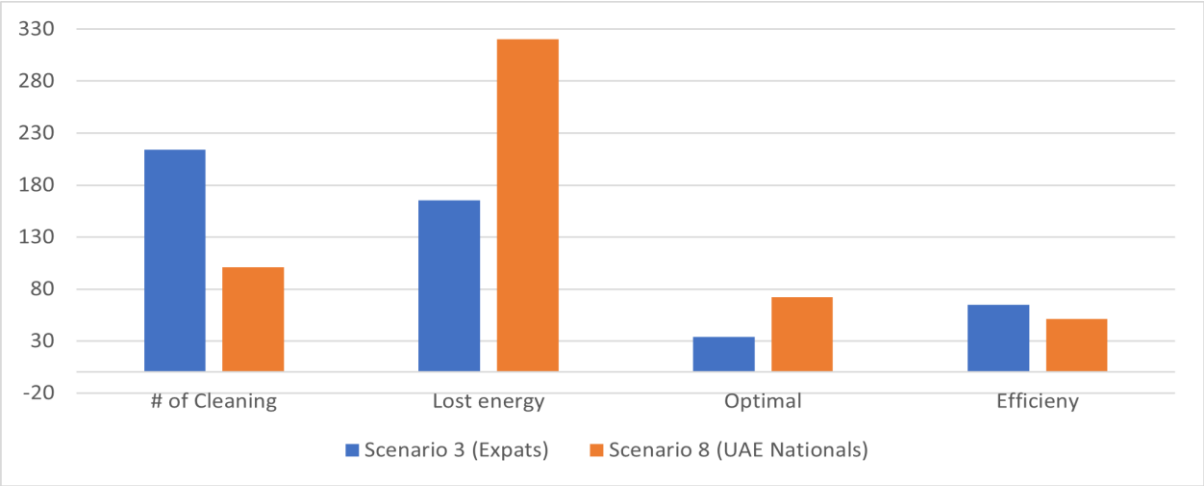

Figure 15: Expats VS UAE nationals comparison considering the Basic model

4.3.4 Reset model

As expected, if natural cleaning is fully considered, cleaning frequency will be considerably longer than that with no natural cleaning. As shown in Table 7, the optimal cleaning intervals are longer for the same values of cleaning cost and electricity tariff.

Table 7: Reset Cleaning model result considering expats tariff (0.073$)

S	# Of Cleaning	Cleaning cost (USD)	Lost Energy kWh	Lost energy cost (USD)	Total Cost (USD)	Optimal Interval	Efficiency (min) (%)
11	35.42	1.3566	78.8522	5.75621	7.11279	45	69.46
12	17.23	0.8320	89.3778	6.52458	7.35655	69	69.29
13	15.13	0.8823	90.4453	6.60251	7.48478	74	68.04
14	10.87	0.7422	94.1385	6.87211	7.61430	89	66.56
15	9.86	0.7720	95.7199	6.98755	7.75958	93	66.25

As can be seen in Figure 16, the curves do not tend to go higher while increasing the cleaning interval like what happened using the Basic model, because the amount of lost energy here is smaller. If the module is not clean for a longer time, high wind speed will do the job at no cost.

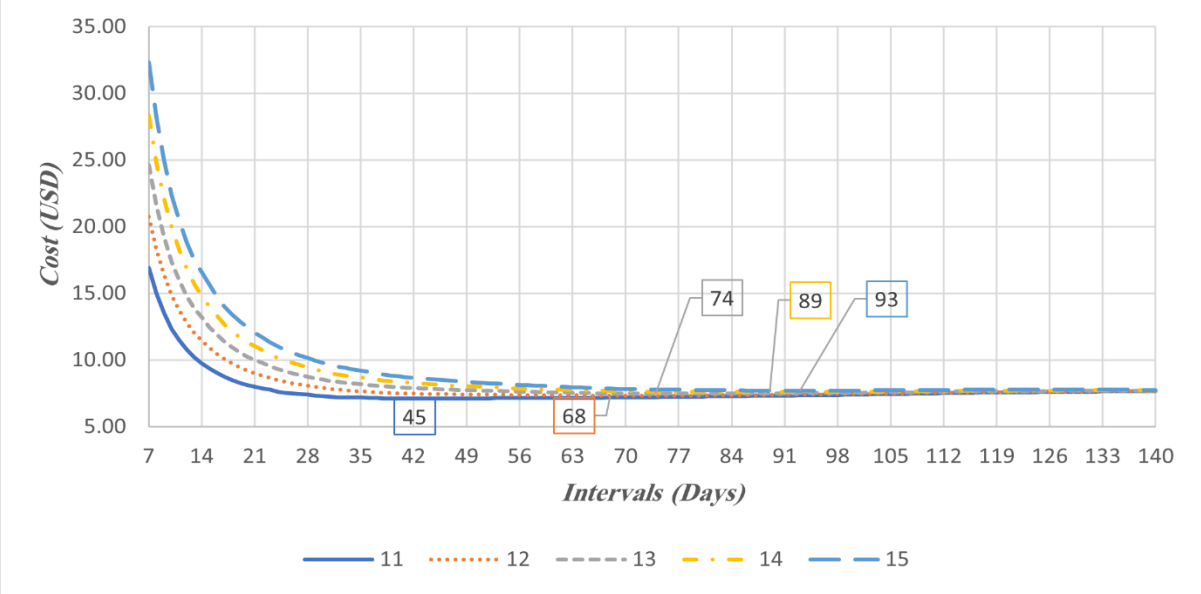

Figure 16: Optimal cleaning intervals for expats tariff and several cleaning cost with Reset model

To emphasize that, further experiments were conducted using UAE nationals' electricity tariff. These time intervals were tested up to 365 days. The resulted optimal intervals were very high. As shown in Table 8, 223 days for all cleaning costs tested, except for 0.0383 USD in S16, which was 239 days. Another noticeable thing is that the efficiency does not go below a certain limit (64 percent), even though the panel is not cleaned for a long time.

Furthermore, the average number of cleanings is approximately zero, resulting in a very low cleaning cost, which does not contribute to the total cost as much as the cost of the lost energy.

Table 8: Reset model result considering UAE nationals tariff (0.018$)

S	# Of Cleaning	Cleaning cost (USD)	Lost Energy kWh	Lost energy cost (USD)	Total Cost (USD)	Optimal Interval	Efficiency (min) (%)
16	0.0429	0.0016	105.68	1.9023	1.9039	239	64.37
17	0.0294	0.0014	105.95	1.9070	1.9085	223	65.43
18	0.0294	0.0017	105.95	1.9070	1.9088	223	65.43
19	0.0294	0.0020	105.95	1.9070	1.9091	223	65.43
20	0.0294	0.0023	105.95	1.9070	1.9093	223	65.43

Figure 17 provides information considering the 13th scenario, in which the actual value for the cleaning cost and electricity tariff (expats) were utilized. It shows how the efficiency is maintained above a certain limit and consequently, the cost of lost energy does not exceed a set threshold despite increasing the interval. This implies that when adopting long intervals, with the Reset model, cleaning may not be required frequently. Most probably, there will be high wind speed during long intervals.

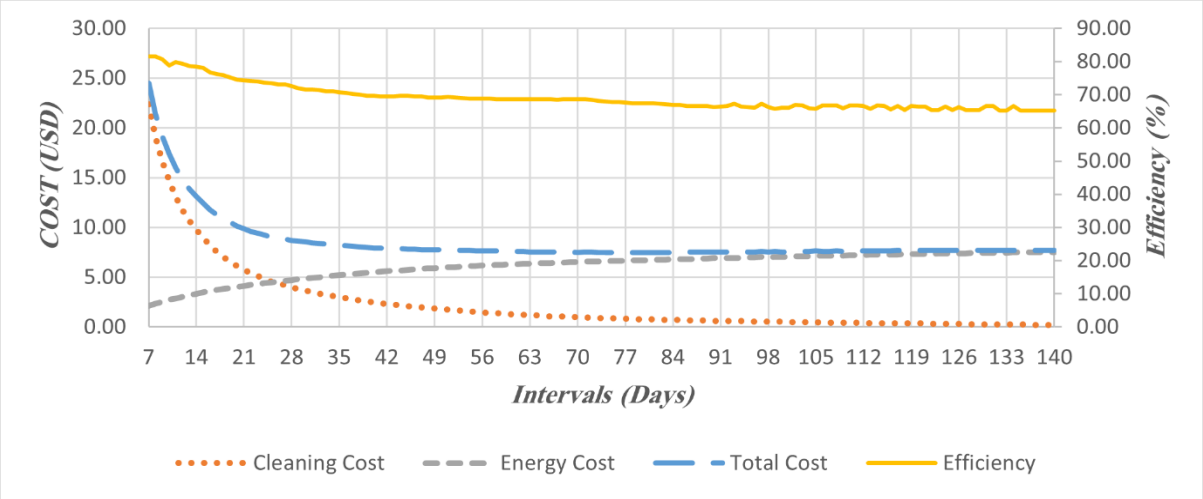

Figure 17: Simulation Output of the typical scenario (S13) for the Reset model

The cost comparison between the two models is shown in Figure 18. It is clearly seen that all costs derived are higher when using the Basic model. Also, cleaning cost considering the Reset model is very low even for expats, because of the very few numbers of cleaning required, and that is obviously seen in Table 9 (15, and zero times for expats and UAE Nationals respectively).

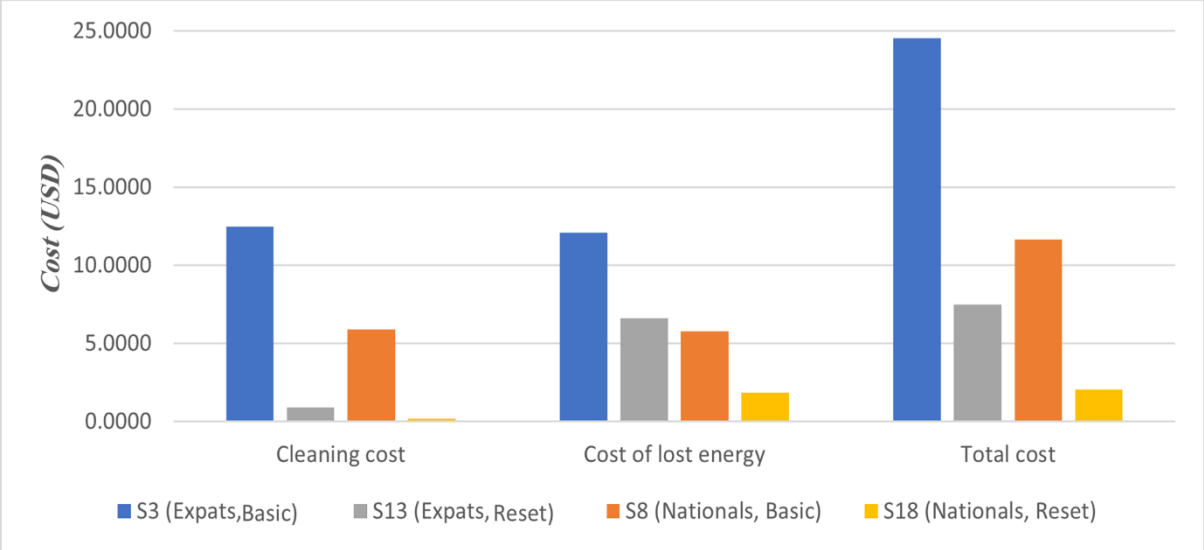

Figure 18: Cost comparison between the Basic and Reset models

Table 9: Comparison of calculated metrics for S3, S8, S13, and S18

Scenario	***# Of Cleaning***	***Lost energy (kWh)***	***Optimal (Days)***	***Efficiency (min) (%)***
S3	214	165.3726	34	64.63
S8	101	320.1589	72	51.13
S13	15.13	90.4453	74	68.04
S18	0.0294	105.95	223	65.43

4.4 Additional Analysis

4.4.1 Natural cleaning effect

The efficiency and the total cost of S13 that were discussed in Figure 17, are further investigated using the box plot in Figure 19, A and B. Figure A verifies that an average efficiency of 64% is maintained across most of the 71 replications performed, with a range of 19. Except for three replications that were designated outliers. In addition, the shape is skewed to the right.

The natural cleaning increases the efficiency by approximately 14% compared to 50% efficiency associated with the same cleaning schedule (74-day interval) when utilizing the Basic model, as can be seen in Figure 13.

On the other hand, the total cost (in graph B), contains only one outlier, and it is more symmetrical around the mean despite the skewness of the efficiency. Which supports the selection of the optimal cleaning interval.

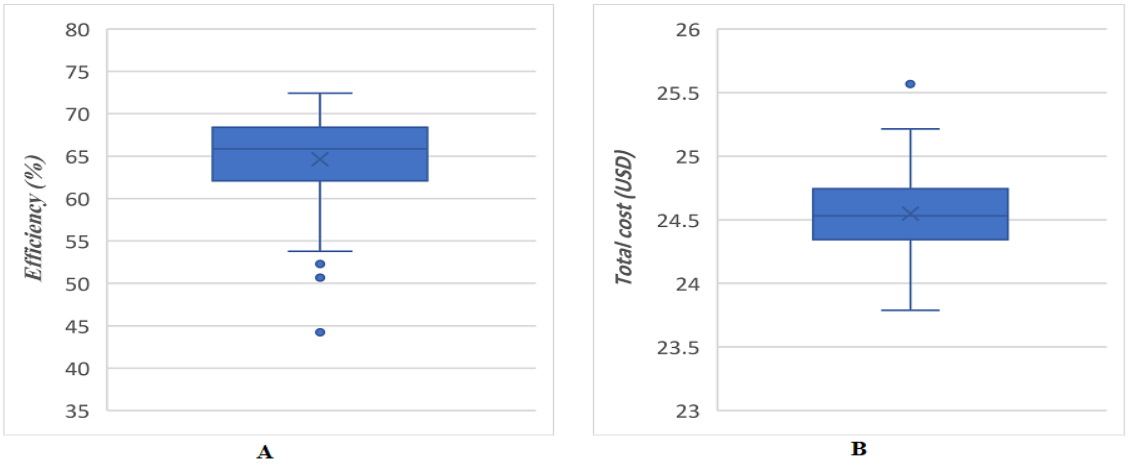

Figure 19: Accuracy of efficiency and total cost

Further investigation of the total cost is depicted in Figure 20 A and B. Considering the Basic model (S3), the total cost is made up of approximately balanced amounts of cleaning cost and lost energy cost (chart A), whereas in the Reset model (S13), it is mostly built up of the lost energy cost (chart B). Not to mention being considerably less than that of the Basic model. That supports the conclusion made in the previous sections (4.3.3 and 4.3.4), that when considering the natural cleaning, weather conditions can restore the module performance at no cost, without the need for frequent cleaning, resulting in reducing the total cost to around one third of that of the Basic model.

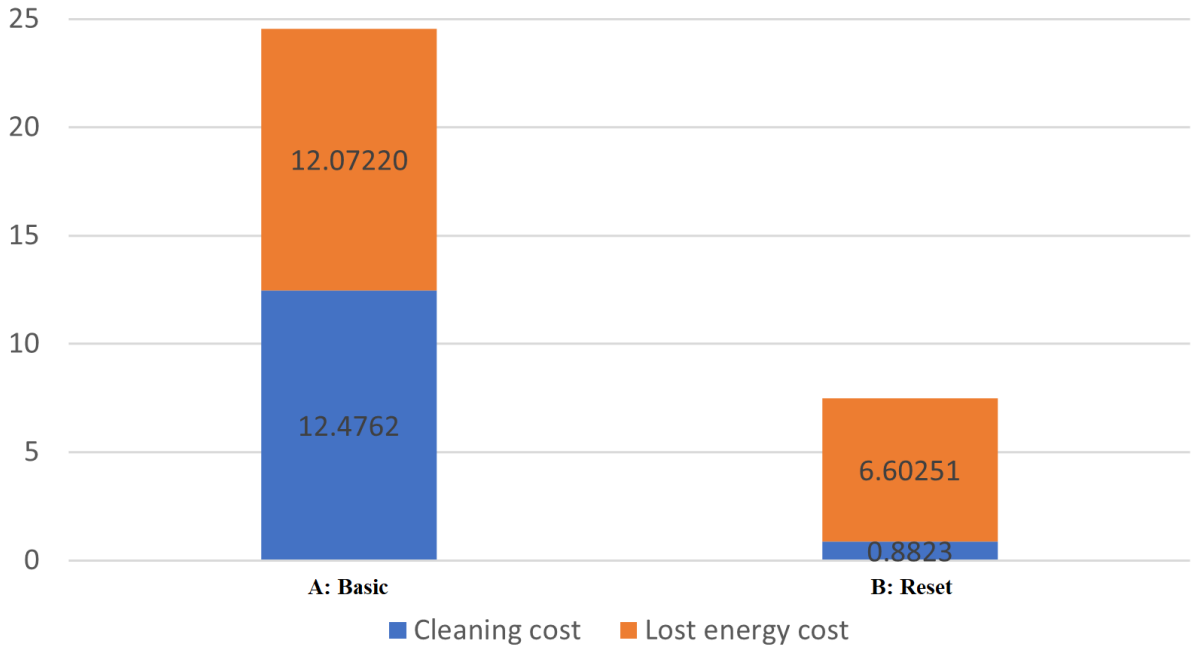

Figure 20: Total cost components at the optimal cleaning frequency (S3 and S13)

4.4.2 Sensitivity Analysis

To investigate the impact of increasing or decreasing the cleaning cost or electricity tariff on the optimal cleaning interval, several values for these costs were examined, as shown in Figure 21 and Figure 22, considering the Basic and Reset models, S3 and S13 respectively. And the corresponding optimal frequencies for all combinations were determined.

The Basic model graph demonstrates that the ideal cleaning interval decreases when the cleaning cost is lower and the electricity rate is higher, and it increases when the cost of cleaning is higher, and the rate is lower. The same applies when the Reset model is utilized, except in the case when using electricity tariff that is less than half of that of expats, which results in a relatively long cleaning intervals (223 days).

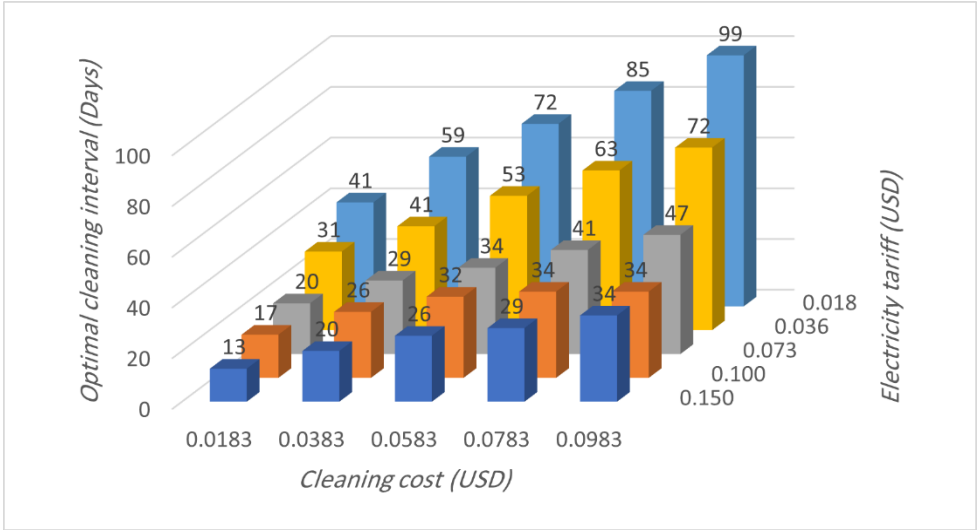

Figure 21: Basic model sensitivity analysis

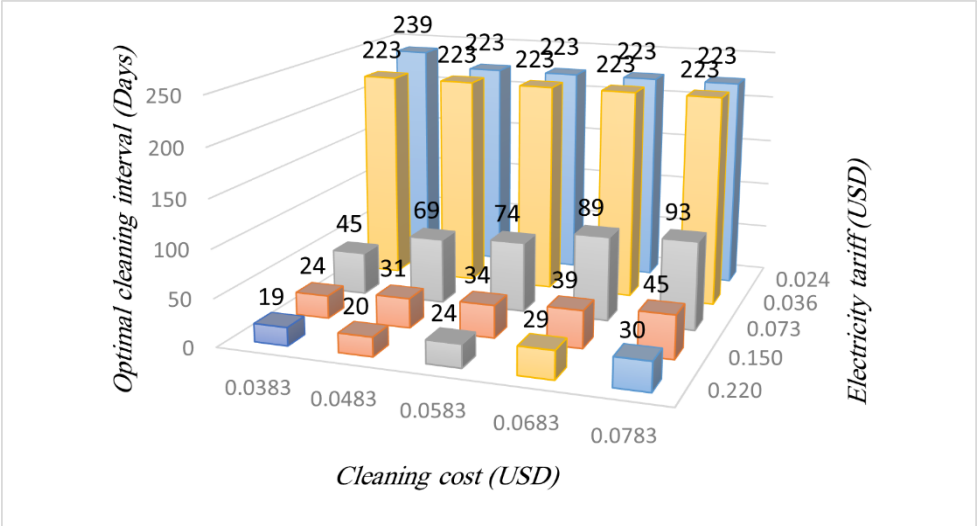

Figure 22: Reset model sensitivity analysis

4.4.3 Excel result VS Simulation result

Table 10 compares the 34-day policy resulting from the simulation to the 45-day policy resulting from Excel. However, all metrics have been calculated using the simulation tool, and are related to S3. As can be seen from the table, the difference in the total cost between the two schedules is 0.5 USD only. However, using the 34-day policy can save 48.4 kWh. In addition, the simulation result is based on a 20-year data set, as opposed to the calculations performed in Excel, which only use a 3-year data set.

Table 10: Excel VS simulation

Interval (Days)	# Of Cleaning	Cleaning cost (USD)	Lost Energy kWh	Lost energy cost (USD)	Total Cost (USD)
34	214	12.4762	165.4	12.0722	24.5484
45	162	9.4446	213.8	15.6066	25.0512

Chapter 5. Discussion

As per the analysis in the previous section, dust can really be a major hindrance to an effective solar panel, and its impact varies depending on time and location. If not cleaned properly, it might limit or completely disable the panel's operation: 3.728 g/m^2 of dust accumulation results in 0% efficiency.

According to the Regulation & Supervision Bureau [RSB] (2017), the Abu Dhabi government recommends four weeks of periodic cleaning to restore efficiency. However, their recommendation does not account for the daily variation in key parameters such as weather conditions and the cost of cleaning or electricity tariff. The outcomes of this study are based on real weather data and financial analysis for the consequences of cleaning or leaving the module dirty. Considering the proposed cleaning cycle, the annual cost will be lower, especially if a large number of solar modules is considered.

As well as bringing the dust, the wind can remove it too, but that depends on its speed and the adhesion force between dust particles and the module surface, which can be very strong if the humidity is high. Therefore, two simulation models have been developed, one that considers the full effect of the high-speed wind on the dust removal process, and the other one only considers that effect partially. The use of the simulation tool facilitated not only the implementation of these two logics; but also, the generation of thousands of data points and the testing of tens of scenarios, all of which had a significant effect on the accuracy and reliability of the results.

As per the results, expats should clean their modules more frequently than UAE nationals; the interval is almost half of that for citizens. When considering the natural cleaning by the high-speed wind, no cleaning strategy is recommended for UAE nationals, since they can purchase electricity from the grid at a lower price if their system’s performance goes low and does not get restored naturally, whilst expats have to clean their modules in the specified periods.

The efficiency degradation is not linear with dust deposition and adopting the specified frequencies does not guarantee the highest efficiency rather than ensuring it is the most economically effective option. Although these results are based on a 20-year simulation, massive dust deposition or removal can happen between any two cleaning cycles. However, the result obtained remains the best considering normal situations.

Furthermore, the type of cleaning technique would be just a matter of cleaning cost, if every technique guarantees that the full performance of the module will be restored. Therefore, only manual cleaning has been considered in this research. In addition, rainfall, which other research proved that it has a good impact on the dust removal process (according to Javed et al. (2020); it can fully clean the module if it exceeds 3mm/day), was not included in this analysis, because it is very rare in UAE.

The outcomes of this research are region-specific. However, they can be a good estimate for the surrounding cities with similar weather. Also, the data analysis framework is generic and can be applied anywhere, processing the data from that place, and determining the corresponding metrics. Furthermore, the methodology followed to calculate the dust accumulation is not inclusive of PV modules only. It can be used for any surface with a similar structure.

To sum up, for most residents, a cleaning cycle of 34 days is the optimum option to get the highest value of a PV system. However, if a natural cleaning (by a high wind speed) is considered in the cleaning policy, the interval could be increased almost up to double.

Chapter 6. Conclusion, Limitations, and Future Work

This research aims to determine the optimal cleaning frequency for PV modules mounted in the Abu Dhabi area, considering the financial implications of the selected interval.

The research required a thorough understanding of the weather conditions in the area. Therefore, it started with analyzing the historical data of dust and other weather parameters in the region. Then a systematic approach was followed to determine the best cleaning frequency, starting with quantifying the amount of dust that accumulates daily on the module and greatly affect the solar system's performance. Based on that, the reduction in the generated energy was calculated and priced, considering that the lost energy due to this soiling will be compensated for by the grid.

Then, preliminary examinations were conducted in Excel. Together with the actual cleaning cost and electricity tariff, several values for cleaning intervals were tested, and their impact on the lost energy was quantified. Although frequent cleaning enhanced the efficiency, it derived more costs. Therefore, a trade-off between cleaning cost and the cost of lost energy was conducted followed by a determination of the optimal cleaning interval.

Furthermore, simulation optimization has been utilized to obtain more accurate and robust results, several values for cleaning cost and electricity tariff were tested while adopting different cleaning intervals. The total cost considering each case was computed, and based on it, the optimal frequency was selected.

For expats and UAE nationals, the recommended cleaning frequency is 34 and 74 days, respectively, based on a cleaning cost of 0.03 USD/m^2.

The findings of this study are reliable since they are based on real-world aspects, and the approach followed takes into account the uncertainty associated with meteorological parameters, by utilizing, generating, and processing data with a high level of uncertainty. Furthermore, this research contributes to improving the long-term reliability of existing solar systems, and a better understanding of dust characteristics and their effect on PV modules performance in the UAE and other similar climates.

Moreover, the findings could help with providing useful information for planning, optimizing, and advising appropriate cleaning methods. It is also a good reference for individuals, cleaning companies, manufacturers, system installers, and policy makers.

6.1 Limitations

The study possesses intrinsic limitations as follows:

- Only three-year data was available
- It was not possible to conduct outdoor experiments to measure the accumulation of dust and compare it with the calculated values
- The efficiency formula was designed for a poly-crystalline PV panel. However, there are slight differences between this type and other types like mono-crystalline and thin-film. Therefore, the usage of this formula should be conservative with these types.
- The surface structure and anti-coating of the PV module, as well as the tilt angle and orientation, were not taken into account in the dust accumulation estimates

6.2 Future work

Although this study provides fruitful and valuable outcomes, there is still room for improvement. The region-specific analysis done in this study can be extended to other areas using different data. Also adding more parameters including humidity, rainfall, and precipitation, will enhance the developed method. In addition, using real-time data measurement of the PV module efficiency, AI, and weather forecast can assist in getting more accurate results and determining whether to clean on a specific day or wait until a sandstorm or high-speed wind hits.

Although this study considers a constant interval cleaning strategy, devising different cleaning interval patterns in a different season would be another increasing future research topic.

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Appendices

Appendix A

Table 11 shows the specification of the assumed solar module to be used in the calculations. The size, lifespan, rated power, and efficiency were primarily utilized in the research.

Table 11: Assumed panel specifications

Type	Cell type	Polycrystalline Silicon
Size	Unit cell	156 * 156
Electrical Properties	Unit solar panel system (landscape)	1960(L)*992(W)*40
	No. of cells in a unit	72
	Maximum power at STC	330 W
	Optimum operating voltage	37.5V
	Optimum operating current	8.81A
	Open circuit voltage	46.2 V
	Short circuit current	9.38 A
	Module efficiency	19.2%
	Operating module temperature	(40) to 85
	Maximum system voltage	1500 V DC
	Maximum series fuse	20A
Lifespan		20 years

Appendix B

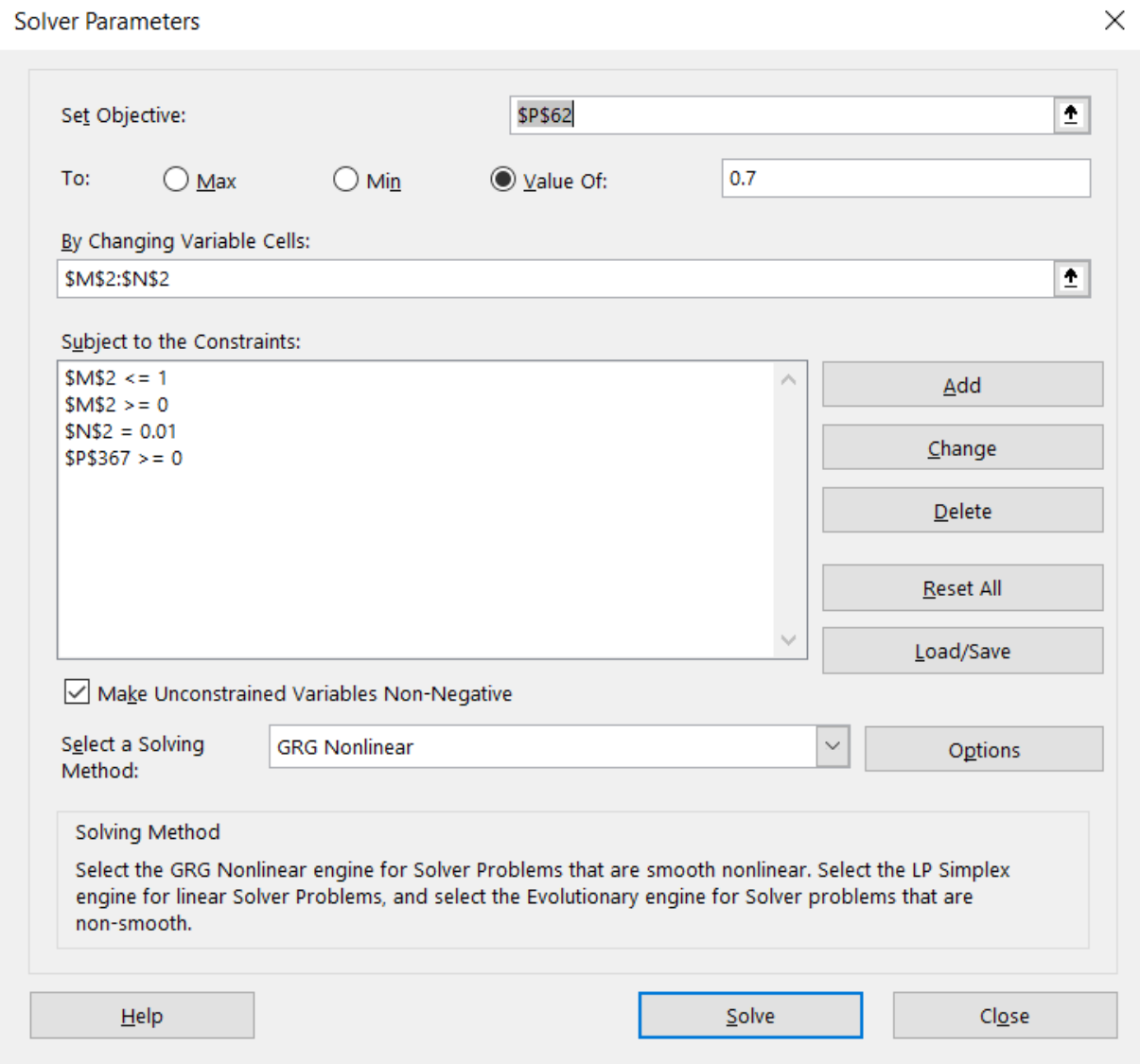

Figure 23: Calibration factor optimization using Excel solver

Objective function:

Reduction in efficiency after two months equals 30%, or in other words, the efficiency on day 60 equals 70% of the module's highest efficiency.

Subject to:

$$0 \leq Calibration\ factor \leq 1 \qquad (11)$$

$$0.1 = Residue \qquad (12)$$

$$0 \leq Efficiency\ of\ the\ last\ day\ (day\ 365) \qquad (13)$$