Extended Essay

Environmental Systems and Societies

The Effect of Dust Accumulation and Cleaning on Solar Panel Performance in Ankara

Word Count: 3957

Table of Contents

Introduction

Mankind has used fossil fuels to cover their energy needs for centuries. But today, the interest in renewable energy sources has increased not only due to the limited sources of fossil fuels but also the environmental pollution, carbon emissions, and consequently, climate change that fossil fuels cause.

In this sense, Turkey, which ranked 15th in the world with 506.1 million tons of CO_2 gas emissions in 2019,[1 2] is increasing investments for the utilization of renewable energy sources instead of fossil fuel in line with the target of zero emission in 2050.[3]

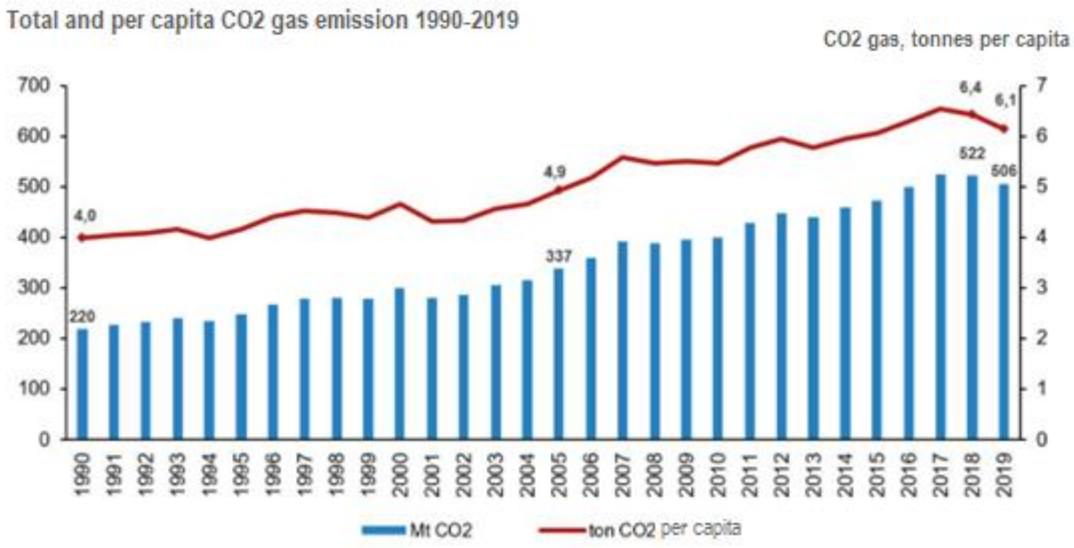

Figure 1. Greenhouse Gas Emission Statistics 1990-2019 [1]

[1]Turkish Statistical Institute (March 2021). *Greenhouse Gas Emission Statistics 1990-2019*.https://data.tuik.gov.tr/Bulten/Index?p=Greenhouse-Gas-Emissions-Statistics-1990-2019-37196

[2]Independent Türkçe (December 2019). *Turkey ranks 15th in the world in terms of carbon emissions*. https://www.indyturk.com/node/100321/%C3%A7evre/t%C3%BCrkiye-karbon-sal%C4%B1n%C4%B1m%C4%B1nda-d%C3%BCnyada-15%E2%80%99inci-s%C4%B1rada

[3] Şahin Ü.,Tör O. B., Kat B., Teimourzadeh S., Demirkol K., Künar A., Voyvoda E., Yeldan E. (October 2021). *Turkey's Decarbonization Pathway: Net Zero in 2050*. IPC-Sabancı University-Stiftung Mercator Initiative, İstanbul.

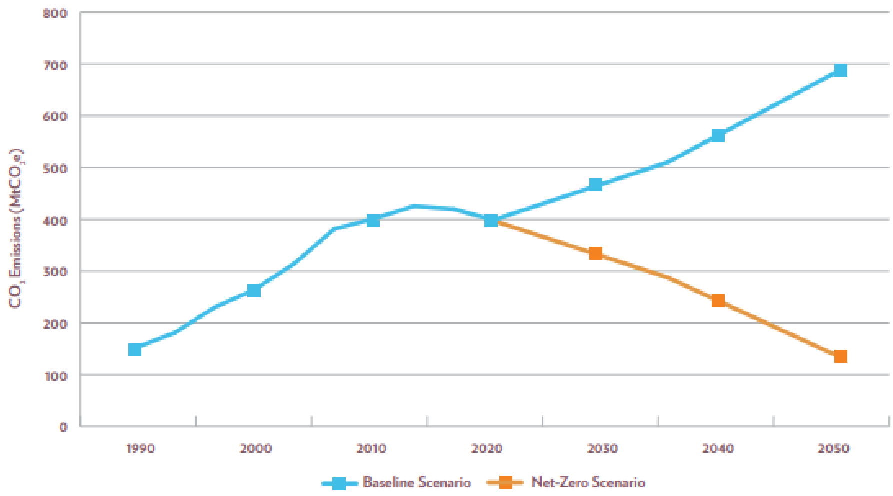

Figure 2. Comparing CO_2 emissions in the Baseline and Net-Zero Scenarios [3]

The use of renewable energy sources is crucial for countries that depend on other countries to cover their energy needs. Turkey supplies 74 percent of its energy from foreign countries which results in increased prices for the citizens.[4] Therefore, for Turkey, apart from the environmental benefits, the increased use of renewable energy provides cost-efficient solutions to the citizens, increasing the welfare of society.

Amongst the many different types of renewable energy sources including biomass, geothermal, and hydropower energy; solar energy is the one that stands out, especially for Turkey. Because Turkey, located between 36° and 42°N latitudes, or the so-called "sunny belt" has a relatively high solar energy potential due to its geographical location, according to the Global Solar Atlas.

[4] Ministry of Foreign Affairs, (n.d). *Turkey's International Energy Strategy*. https://www.mfa.gov.tr/turkeys-energy-strategy.en.mfa

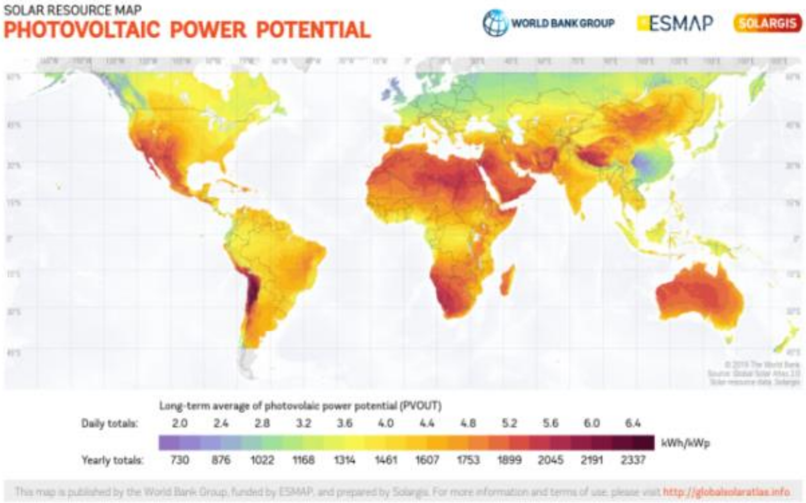

Figure 3. Photovoltaic Power Potential
Source: Solgaris, World Bank Group, "Global Solar Atlas" https://globalsolaratlas.info/global-pv-potential-study

With the latest technological developments, the cost of solar energy has decreased by 89 percent in the last 10 years.[5] The investment costs of solar technologies are expected to decrease significantly in the coming years. The materials used in the manufacturing of solar panels are mainly recycled products, so the carbon footprint of solar panels is already quite small.[6] It can be said that solar energy being safe, abundant, and cost-efficient plays a major role in providing clean and renewable energy to both developing and developed countries, with Turkey being a prime example, while bearing a significant impact on the reduction of CO_2 emissions.

There is a considerable increase in the utilization of solar energy in the recent years in Turkey, a trend that is noticeable in many nations across the globe. The first phase of Turkey's biggest solar plant, with a total capacity of 271 megawatts, has been recently finalized in 2021.[7]

[5] Roser M. (December 2020). *Why did renewables become so cheap so fast?* Our World in Data. https://ourworldindata.org/cheap-renewables-growth

[6] TreeHugger (2021). *What Is the Carbon Footprint of a Solar Panel? Overview and Emissions*. https://www.treehugger.com/how-much-co-does-one-solar-panel-create-4868753

[7] Şengül E. (2021). *Turkey finalizes first phase of Turkey's biggest solar power plant*. Anadolu Agency Energy. https://www.aa.com.tr/en/energy/invesments/turkey-finalizes-first-phase-of-turkeys-biggest-solar-power-plant/32937

Moreover, roof-type residential solar panels are becoming popular amongst the domestic users as a result of increased prices of conventional electricity.

The most widespread way of collecting solar energy is by using Photovoltaic (PV) solar technologies. Solar PV technologies are generally employed on a panel, hence the name solar panels. Solar panels convert sunlight directly into electricity by using semiconductors. To put it simply, when the sun hits the semiconductor inside the PV cell, electrons are released and current is created. The performance of a solar panel is measured by the electrical power it produces.[8]

Unfortunately, there are some limitations which decrease the performance of solar panels. Contamination of panels is one of the main concerns that may cause a significantly deteriorate the performance of solar panels. One of the most important sources of contamination is dust accumulating on the panels. Dust, either natural or anthropogenic, spreads to the atmosphere via wind or precipitation and then settles on the solar panels, reducing the radiation the panels receive.

Dust accumulation is known as a function of certain environmental and weather conditions. For example, in England, one of the most dust-free regions in the world, the dust accumulated on the panels for one month reduces the solar radiation 5-6%. To put that into perspective, dust accumulation in Sudan was 9 times higher than in England. In many parts of the world, large-scale solar power plants are installed in areas with high solar radiation, mostly in desert regions where sandstorms can cause a thick layer of dust to be accumulated on solar panels within an hour and can lead to a 70-80% reduction in electrical power output. [9] If the panels

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[8] Student Energy (n.d). *Solar PV.* https://studentenergy.org/conversion/solar-pv

[9] Genç G. (2018). *Analysis Of Dust And Shadow Effect On Photovoltaic Modules*, Hacettepe University, Ankara

are left untouched, the panels may lose effectiveness and even become useless. In this context, cleaning appears to be a viable process to increase the performance of solar panels.

In this study, I decided to conduct an experiment to investigate the effect of manual cleaning of the dust accumulated on the solar panels on their performance. In order to observe the effects of cleaning more clearly, I planned to compare the results of cleaning done with different periods throughout 12 weeks, the duration of the experiment.

The experiment was designed with the aim of answering the following research question and testing the hypothesis below:

Research Question:

"To what extent does the cleaning period of dust on solar panel (one week, two weeks, three weeks, four weeks and none for a timeframe of 12 weeks) affect its electrical power performance ?”

Hypothesis:

The cleaning period and the power output of the solar panels are inversely proportional. The power output of the panels that are cleaned every week will be higher than the others with longer cleaning periods. For the panels left uncleaned, the performance will be the minimum.

The results of this investigation are important because Turkey possesses a high potential for solar energy but also has high levels of dusting. Due to its geographical location, Turkey is affected by desert dust originating from Africa and the Middle East, where dust is in abundance.[10] In addition, being a developing country, high levels of anthropogenic dust

[10] Meteoroloji Genel Müdürlüğü (2021). *Türkiye ve Çevresi Toz Taşınımı Analizleri (2003-2020).* https://www.mgm.gov.tr/FILES/genel/raporlar/BatiAsya_2003_2020_TOZ_Degerlendirme_20210116.pdf

can be expected, especially due to abundant construction. This trend was also observed in the experiment since there were more than five construction sites in the immediate vicinity.

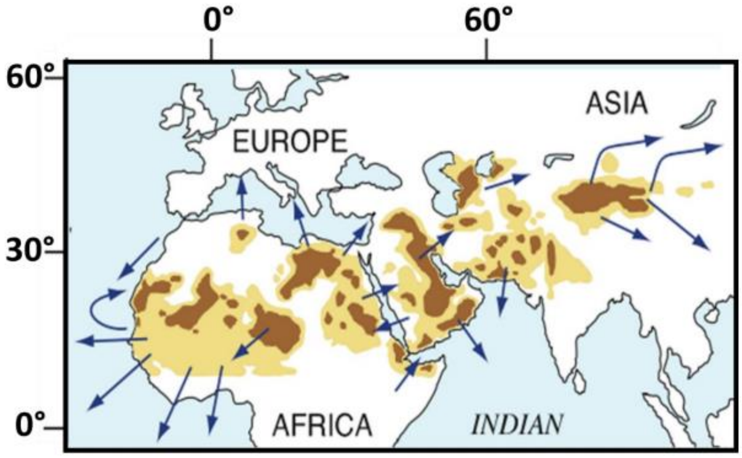


Figure 4. Important Dust Source Areas in Africa, the Middle East and Asia [10]

With this investigation, it is aimed to draw attention to the effect of dust on the performance of solar panel systems and to reveal the effects of cleaning done at different periods on panel performance.

Methodology

Rationale of the Experiment

In this investigation, to observe the effect of manual cleaning of the dust accumulated on the solar panels on their performance, an experiment was conducted. The experiment was performed outdoors, in the garden of my house in Ankara with a test system consisting of 25 mini solar panels.

To examine the effects of cleaning on the performance of solar panels, the panels were divided into five different groups with different cleaning periods set to one week, two weeks, three weeks, four weeks and never cleaned. To reduce random errors in measurement and increase precision, five trials of each set were examined. Therefore, 25 identical solar panels were used. In the experimental set-up given in Figure-5, all solar panels were mounted on a metal plate as close to each other as possible to ensure that they receive equal amounts of sunlight. In order to analyse the effects of dust deposition on the panels more accurately, the experimental period was determined as 12 weeks, and data was collected weekly.

Variables

	Name of Variables	Method of Management and/or Measurement
Independent Variable	Cleaning period (weeks) (1,2,3,4,0/never cleaned)	Since the dust accumulation is intended to be completely natural, no measures were taken in the management of the amount of dust to make the process as authentic as possible.
Dependent Variable	Electrical Power Produced (Watts)	The voltage V (Volts) across a resistor of a defined resistance R (Ohms) is measured. The produced power is calculated using the electrical power equation ($P = \frac{V^2}{R}$).[11]
Controlled Variable	Panel set-up tilt angle	Panel set-up was mounted with a tilt angle which is the optimal angle for Ankara.
	Panel set-up position	In order to prevent the panels from being overshadowed by the surrounding buildings or trees, the set-up was mounted on a spot with clear sky view.
Uncontrolled Variables	Amount of sunshine, ambient temperature, air humidity, precipitation, wind strength	The natural environment has not been interfered with.

Table 1. Experimental Variables

Designing the Experiment Set-up

According to my research about the working principle of solar panels, the performance of a solar panel is expressed in terms of the electrical power it produces.[12] In physics, the electrical

[11] The Physics Hypertextbook (n.d.). *Electric Power*. https://physics.info/electric-power/

[12] TeachEngineering STEM Curriculum for K-12 (n.d).*Pointing at Maximum Power for PV*. .https://www.teachengineering.org/content/cub_/activities/cub_pveff/Attachments/cub_pveff_lesson03_activity1_guide_v11_tedl_dwc.pdf

power generated by an electrical system is calculated by the product of current and voltage produced $\mathrm{P = V * I}$

Applying Ohm's Law, which states that the voltage across a resistor is directly proportional to the current flowing through it ($I = \frac{V}{R}$), and substituting it in the above formula:

$$P = V * I = V * \frac{V}{R} = \frac{V^2}{R}$$

where P is electrical power in $Watts$, V is the voltage in $Volts$, I is the current in $Amps$ and R is resistance in $Ohms$.

In the experiment, to calculate the electrical power produced by the solar panels, it was decided to connect a resistor to the output of each panel, measure the voltage on that resistor, and calculate the power according to the above formula.

To determine the value of the resistor to be connected, the power formula was used. The electrical specifications of chosen panels are given as $1\,Watt/6\,V$ meaning they produce $1\,Watt$ electrical power at an output voltage of 6 Volts. Substituting these values in the formula, the minimum resistance value is calculated as:

$$1\ \mathrm{Watt} = \frac{6^2}{R} = \frac{36}{R} \qquad \mathrm{R = 36\ Ohm}$$

In order to use the panels within the safe operation limits, the resistance value must be chosen larger than this minimum value. Therefore, a resistance of $50\ \mathrm{Ohm}$ was selected since it's a standard resistance value and relatively easy to find. Now, by measuring the voltage across the $50\ Ohm$ resistor with the help of a voltmeter, the power output can easily be calculated.

Since there are a total of 25 panels in the experiment set-up, it means that there are 25 resistors and therefore 25 voltage measurements should be done weekly. Since the experiment duration is 12 weeks, including the initial measurement done at the start of the experiment, $13x25 = 325$ voltmeter readings should be done throughout the experiment. Measuring the voltages manually is not only time consuming but also since measurements cannot be done simultaneously for all panels, it is impossible to provide the same insolation conditions for all panels. For example, there may be momentary clouding during manual voltage measurement. This will cause the power output of that panel to be measured lower than the previously measured panel even if it was cleaner. Therefore, an automatic measurement method was used to prevent these types of errors and to conduct a more reliable and precise experiment.

Being familiar with Arduino boards, which are the most popular easy-to-use hardware and ready-to-use software electronic platforms, I decided to use them for the automated measuring. Arduino Mega, a compact model with 16 voltage inputs, was chosen for this experiment.[13] Since there are 25 solar panels in the panel block set-up, two Arduino Mega boards were used. To capture the data from the Arduino board, a laptop computer with a USB port was added to the set-up system. Termite, a freeware data collection software, was chosen to record the measured data automatically.

The scheme of the final experiment set-up system is given in Figure 5:

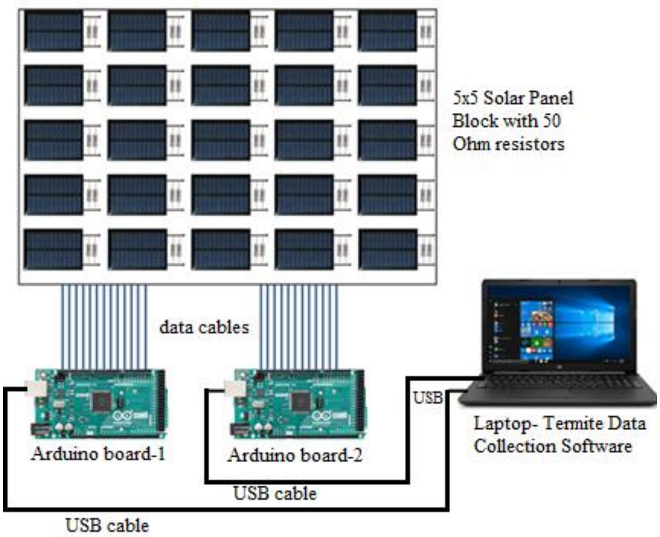


Figure 5. Experiment Set-up Scheme

[13] Arduino Mega 2560 Rev3. (2022). *Datasheet.*
https://docs.arduino.cc/static/dbd0a6eb970881b64825595f507fdce6/A000067-datasheet.pdf

Materials

Material	**Size (± uncertainity)**	**Quantity**
1 Watt/6V Solar Panel Brand: Polaxtor Model: PLX-20144	7 (±0.5) cm x 5 (±0.5) cm	25
Resistance	50 (±%1) Ohm / 1Watt	25
Cable	20 (±1.0) meters	25 pairs
Aluminum plate	60 (±0.5) cm x 45 (±0.5) cm	1
Aluminum Profile for Appropriate Tilt Angle	150 (±1) cm	1
Terminal Block	5(±0.5) cm x 3(±0.5) cm	5
Screw, Nut	miscellaneous	25 set
Laptop with 2 USB ports		1
Termite Freeware Data Collection Software		1
Arduino Mega Board		2
USB Cable		2

Table 2. Experiment Materials

To achieve maximum sunlight absorption, sunlight must reach the panels at a right angle. In order to achieve this, the tilt angle which is the angle between the solar panel and the horizontal plane on which it will be mounted must be adjusted accordingly.

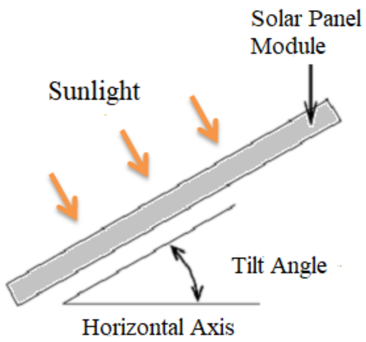


Figure 6. Tilt Angle for Maximum Sunlight Absorption

Since the optimal tilt angle for Ankara is 38 degrees, a custom profile was constructed as given below:[14]

[14] Aydınlatma Portalı. (n.d.). *81 İl için Önerilen Güneş Paneli Eğim Açısı*. https://www.aydinlatma.org/81-il-icin-onerilen-gunes-paneli-egim-acisi.html

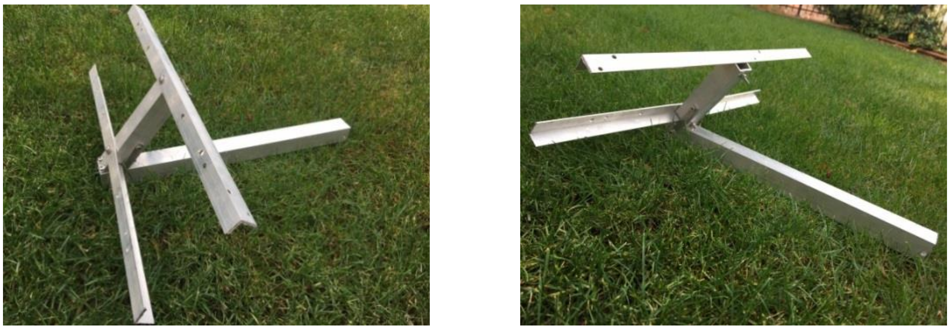


Figure 7. Profile for Appropriate Tilt Angle

Justification

In this experiment, an automated measuring method was used. Because, apart from dust, the most important factor affecting the performance of solar panels is the weather. For weather variations to affect all panels equally, the measurements must be made simultaneously. So, it was decided to make weekly measurements automatically, using appropriate hardware and software support, at 1:00 PM when the sunlight is closest to a right angle. Before starting the experiment, the dust accumulation on the panels was observed for 2 weeks. Daily dust accumulations were minimal, and not sufficient to reach meaningful conclusions. Long periods were considered but were found to be not feasible. Therefore as an optimal value, the minimum cleaning period was chosen as one week and the other periods were taken as integer multiples of this. Experiment duration was decided as 12 weeks which is long enough to observe the effects of dust deposition and cleaning at chosen periods.

Procedure

Construction of Experiment Set-up:

- Mount 25 solar panels in a 5x5 matrix on aluminium plate
- Connect panel outputs to terminal blocks using cable pairs

- Connect 50 Ohm load resistors to terminal blocks
- Connect cable pairs to terminal blocks
- Label panel groups from 1 to 5
- Fix the panel to the aluminium profile constructed for the appropriate tilt angle
- Mount the aluminium set-up on a spot with clear sky view in the garden
- Place the laptop and the Arduino Boards on a table inside the house
- Label the cables with panel numbers and connect other ends to appropriate Arduino voltage input pins and ground pins on the Arduino Boards
- Plug two Arduino Boards (uploaded with analogue to digital conversion code) to the laptop’s USB ports using USB cables.
- Install the freeware data collection software “Termite” on the laptop

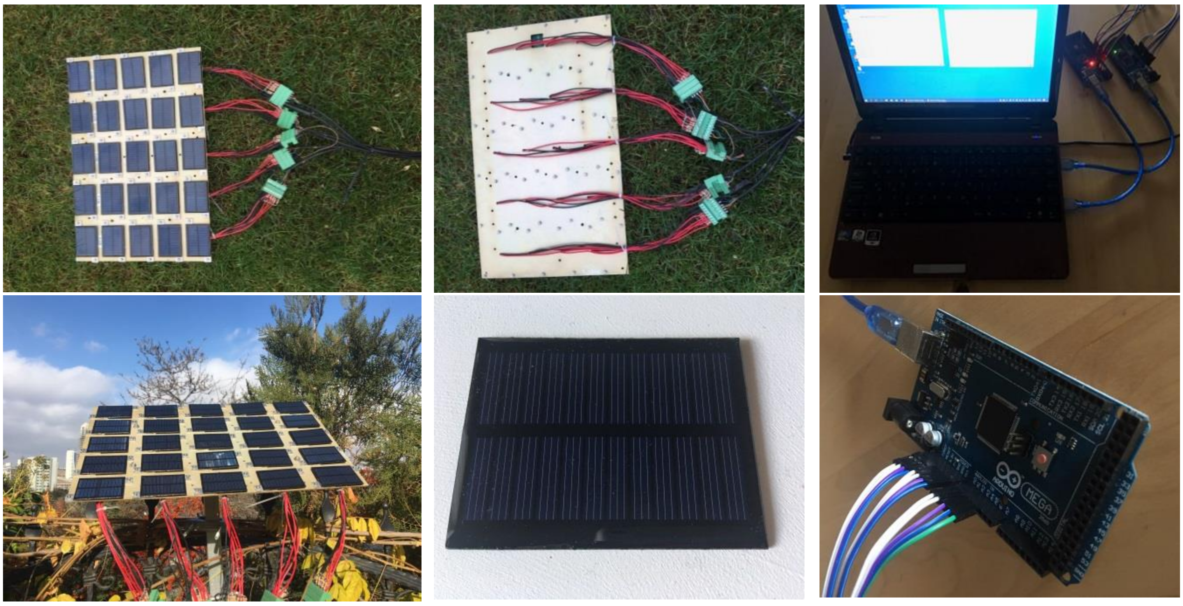


Figure 8. Experiment Set-up

Experimental Procedure:

- Clean all of the panels with a cloth damped with tap water
- Turn on the Arduino Boards and the laptop and run the data collection software prior to data collection time 1:00 PM
- Ensure that the data is collected by Termite software
- Record the data at 1:00 PM with date information
- Turn off the Arduino Boards and the laptop
- Clean the solar panel groups with a damp cloth at the intervals specified in Table 3. To be sure to clean panels after data collection is completed
- Continue experiment for 12 weeks

Solar Panel Sets	Cleaning Period
SET-1	1 week
SET-2	2 weeks
SET-3	3 weeks
SET-4	4 weeks
SET-5	0, do not clean

Table 3. Panel Cleaning Period

Risk Assessment and Ethical Considerations

All of the electronic components used in the experiment (solar panels, Arduino boards, laptop, resistors and cables) are CE certified, meaning that they meet EU safety, health and environmental protection requirements. The experiment setup was modified after the experiment and is being used in the garden entrance lighting of our house.

Data Collection, Processing and Analysis

Raw Data

The weekly measured voltage data is given below. Since Arduino Board voltage inputs have ~5mV resolution, the uncertainty in voltage measurement is taken as ±0.005 volts.[15]

Voltage Measured on 50 Ohm Load Resistor (volt / ±0.005)														
Cleaning Period (weeks)	**Trials**	**Week0**	**Week1**	**Week2**	**Week3**	**Week4**	**Week5**	**Week6**	**Week7**	**Week8**	**Week9**	**Week10**	**Week11**	**Week12**
1	1	4.28	2.66	4.15	4.22	4.15	4.30	3.87	4.29	4.19	4.01	3.89	3.48	3.54
(SET-1)	2	4.28	2.74	4.19	4.27	4.21	4.33	3.93	4.35	4.27	4.07	3.91	3.52	3.58
	3	4.32	2.71	4.24	4.31	4.18	4.37	3.96	4.35	4.26	4.08	3.92	3.48	3.58
	4	4.36	2.70	4.28	4.35	4.29	4.43	3.94	4.36	4.27	4.09	3.96	3.54	3.62
	5	4.36	2.71	4.23	4.35	4.25	4.41	3.94	4.35	4.25	4.14	3.97	3.55	3.61
2	1	4.32	2.69	4.20	4.34	4.22	4.40	3.87	4.35	4.20	4.08	3.94	3.52	3.55
(SET-2)	2	4.32	2.69	4.16	4.30	4.15	4.38	3.86	4.34	4.19	4.10	3.83	3.52	3.58
	3	4.31	2.59	4.16	4.27	4.14	4.33	3.88	4.28	4.15	4.04	3.84	3.48	3.53
	4	4.32	2.66	4.18	4.31	4.17	4.38	3.89	4.35	4.24	4.08	3.90	3.52	3.60
	5	4.26	2.64	4.16	4.21	4.13	4.27	3.83	4.31	4.11	4.06	3.85	3.46	3.52
3	1	4.29	2.65	4.18	4.23	4.17	4.31	3.87	4.34	4.17	3.98	3.89	3.45	3.55
(SET-3)	2	4.33	2.66	4.17	4.24	4.23	4.34	3.87	4.37	4.24	4.02	3.99	3.49	3.54
	3	4.29	2.64	4.18	4.23	4.17	4.33	3.85	4.32	4.19	3.96	3.90	3.50	3.53
	4	4.32	2.60	4.14	4.19	4.21	4.34	3.84	4.32	4.20	4.01	3.90	3.44	3.51
	5	4.27	2.65	4.18	4.20	4.17	4.30	3.80	4.28	4.13	3.92	3.89	3.42	3.48
4	1	4.32	2.64	4.18	4.21	4.10	4.36	3.88	4.28	4.10	4.05	3.88	3.43	3.47
(SET-4)	2	4.28	2.64	4.16	4.20	4.09	4.35	3.87	4.23	4.10	4.07	3.89	3.43	3.52
	3	4.31	2.68	4.17	4.22	4.09	4.34	3.88	4.24	4.11	4.07	3.87	3.41	3.45
	4	4.25	2.62	4.16	4.20	4.06	4.33	3.85	4.18	4.09	4.04	3.84	3.42	3.48
	5	4.35	2.71	4.24	4.30	4.16	4.44	3.93	4.29	4.18	4.10	3.91	3.47	3.52
0	1	4.35	2.66	4.18	4.22	4.09	4.20	3.77	4.11	3.99	3.78	3.65	3.20	3.28
(SET-5)	2	4.33	2.66	4.18	4.15	4.04	4.16	3.67	4.05	3.93	3.70	3.57	3.15	3.19
	3	4.31	2.63	4.14	4.25	4.10	4.23	3.75	4.09	3.96	3.75	3.61	3.21	3.24
	4	4.24	2.61	4.12	4.15	4.04	4.15	3.67	4.03	3.89	3.70	3.56	3.16	3.21
	5	4.30	2.65	4.17	4.13	4.09	4.23	3.73	4.08	4.00	3.78	3.59	3.17	3.23

Table 4. Voltage Measured on 50 Ohm Load Resistor

[15] Arduino Reference (n.d.). *AnalogRead.* https://www.arduino.cc/reference/en/language/functions/analog-io/analogread/

Figure 9. Dust Accumulation on Solar Panels

To reduce random measurement errors, the average of the 5 trials is calculated using the general arithmetic mean formula:

$$\overline{V} = \frac{\sum_{i=0}^{n} V_i}{n}$$

Absolute uncertainty and percentage uncertainty are calculated by:

$$\overline{\Delta V} = \frac{\text{voltage\_max} - \text{voltage\_min}}{2}$$

$$\%\overline{\Delta V} = \frac{\overline{\Delta V}}{\overline{V}} x100$$

Standard Deviation of the trials is calculated using the formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (V_i - \overline{V})^2}{n}}$$

where n is the number of trials which is 5, $\overline{V}$ is the arithmetic mean, and V_i is the raw data measured.

Example calculation for SET-1 at week 4;

$$\overline{V_{avg}} = \frac{(4.150 + 4.210 + 4.180 + 4.290 + 4.250)}{5} = 4.216$$

$$\overline{\Delta V} = \frac{4.290-4.150}{2} = \frac{0.140}{2} = 0.070$$

$$\%\overline{\Delta V} = \frac{0.07}{4.216} x100 \cong 1.7\%$$

$$\overline{V_{avg}} \pm \overline{\Delta V} == 4.216 \pm 0.070 = 4.216 \pm 1.7\% \, Volt$$

$$\sigma = \sqrt{\frac{(4.150-4.216)^2+(4.210-4.216)^2+(4.180-4.216)^2+(4.290-4.216)^2+(4.250-4.216)^2}{5}} = 0.050$$

Processed Data

Standard Deviation of Voltage Measured on 50 Ohm Load Resistor													
Cleaning Period (weeks)	**Week0**	**Week1**	**Week2**	**Week3**	**Week4**	**Week5**	**Week6**	**Week7**	**Week8**	**Week9**	**Week10**	**Week11**	**Week12**
1 (SET-1)	0.036	0.026	0.044	0.050	0.050	0.048	0.031	0.025	0.030	0.042	0.030	0.029	0.028
2 (SET-2)	0.030	0.017	0.032	0.031	0.037	0.035	0.031	0.004	0.026	0.025	0.023	0.024	0.025
3 (SET-3)	0.020	0.009	0.040	0.021	0.050	0.021	0.041	0.006	0.033	0.022	0.050	0.024	0.025
4 (SET-4)	0.022	0.044	0.045	0.032	0.058	0.034	0.035	0.029	0.043	0.032	0.060	0.024	0.034
0 (SET-5)	0.017	0.042	0.027	0.029	0.042	0.028	0.028	0.027	0.036	0.032	0.055	0.022	0.030

Table 5. Standard Deviation of Voltage Measured on 50 Ohm Load Resistor

Percentage Uncertainty of Voltage Measured on 50 Ohm Load Resistor (%)													
Cleaning Period (weeks)	**Week0**	**Week1**	**Week2**	**Week3**	**Week4**	**Week5**	**Week6**	**Week7**	**Week8**	**Week9**	**Week10**	**Week11**	**Week12**
1 (SET-1)	0.9	1.5	1.5	1.5	1.7	1.5	1.1	0.8	0.9	1.6	1.0	1.0	1.1
2 (SET-2)	0.7	1.9	0.5	1.5	1.1	1.5	0.8	0.8	1.6	0.7	1.4	0.9	1.1
3 (SET-3)	0.6	1.7	0.5	1.4	0.0	0.9	1.2	0.8	1.3	2.3	0.1	1.4	1.7
4 (SET-4)	0.9	0.8	0.2	1.3	2.1	0.6	0.5	2.2	1.8	0.5	1.9	1.6	2.2
0 (SET-5)	1.3	0.9	0.7	1.4	0.7	1.0	1.3	1.0	1.4	1.1	1.3	0.9	1.4

Table 6. Percentage Uncertainty of Voltage Measured on 50 Ohm Load Resistor

When Table 6 was examined, it was observed that the percentage uncertainty values range between 0.2% and 2.3%, which is a relatively low value. For the error propagation in the calculations, it was decided to use the maximum percentage uncertainty value (2.3%).

The average voltage values for all sets are:

Average of Voltage Values Measured (volt/±2.3%)													
Cleaning Period (weeks)	**Week0**	**Week1**	**Week2**	**Week3**	**Week4**	**Week5**	**Week6**	**Week7**	**Week8**	**Week9**	**Week10**	**Week11**	**Week12**
1 (SET-1)	4.320	2.704	4.218	4.300	4.216	4.368	3.928	4.340	4.248	4.078	3.930	3.514	3.586
2 (SET-2)	4.306	2.654	4.172	4.286	4.162	4.352	3.866	4.326	4.178	4.072	3.872	3.500	3.556
3 (SET-3)	4.300	2.640	4.170	4.218	4.190	4.324	3.846	4.326	4.186	3.978	3.914	3.460	3.522
4 (SET-4)	4.302	2.658	4.182	4.226	4.100	4.364	3.882	4.244	4.116	4.066	3.878	3.432	3.488
0 (SET-5)	4.306	2.642	4.158	4.180	4.072	4.194	3.718	4.072	3.954	3.742	3.596	3.178	3.230

Table 7. Average of Voltage Values Measured on 50 Ohm Load Resistor

Since the performance of solar panels is expressed in terms of the electrical power, it is necessary to calculate the electrical power for each voltage value in Table 7 using the formula

$$P = \frac{V_{avg\_measured}^2}{50\ Ohm}$$

The 50 Ohm resistors used are of type 1%, having a tolerance of 1% which means their uncertainty is 1%.

The resultant power uncertainty is calculated as:

$$\%\ uncertainty\ of\ power = 2\ x\ \%\ \ uncertainty\ of\ voltage + \%\ uncertainty\ of\ resistance$$

Example power calculation is done for SET-1 measured at week 4:

$$V = 4.216 \pm 2.3\%\ Volt$$

$$R = 50 \pm 1\%\ Ohm$$

$$P = \frac{(4.216)^2}{50} = \frac{17.775}{50} = 0.355\ Watt$$

$\% \Delta P = 2x\ 2.3\% + 1\% = 5.6\%$

$P \mp \Delta P = 0.355 \mp 5.6\%\ Watt$

Electrical Power (Watt/±5.6%)													
Cleaning Period (weeks)	**Week0**	**Week1**	**Week2**	**Week3**	**Week4**	**Week5**	**Week6**	**Week7**	**Week8**	**Week9**	**Week10**	**Week11**	**Week12**
1 (SET-1)	0.373	0.146	0.356	0.370	0.355	0.382	0.309	0.377	0.361	0.333	0.309	0.247	0.257
2 (SET-2)	0.371	0.141	0.348	0.367	0.346	0.379	0.299	0.374	0.349	0.332	0.300	0.245	0.253
3 (SET-3)	0.370	0.139	0.348	0.356	0.351	0.374	0.296	0.374	0.350	0.316	0.306	0.239	0.248
4 (SET-4)	0.370	0.141	0.350	0.357	0.336	0.381	0.301	0.360	0.339	0.331	0.301	0.236	0.243
0 (SET-5)	0.371	0.140	0.346	0.349	0.332	0.352	0.276	0.332	0.313	0.280	0.259	0.202	0.209

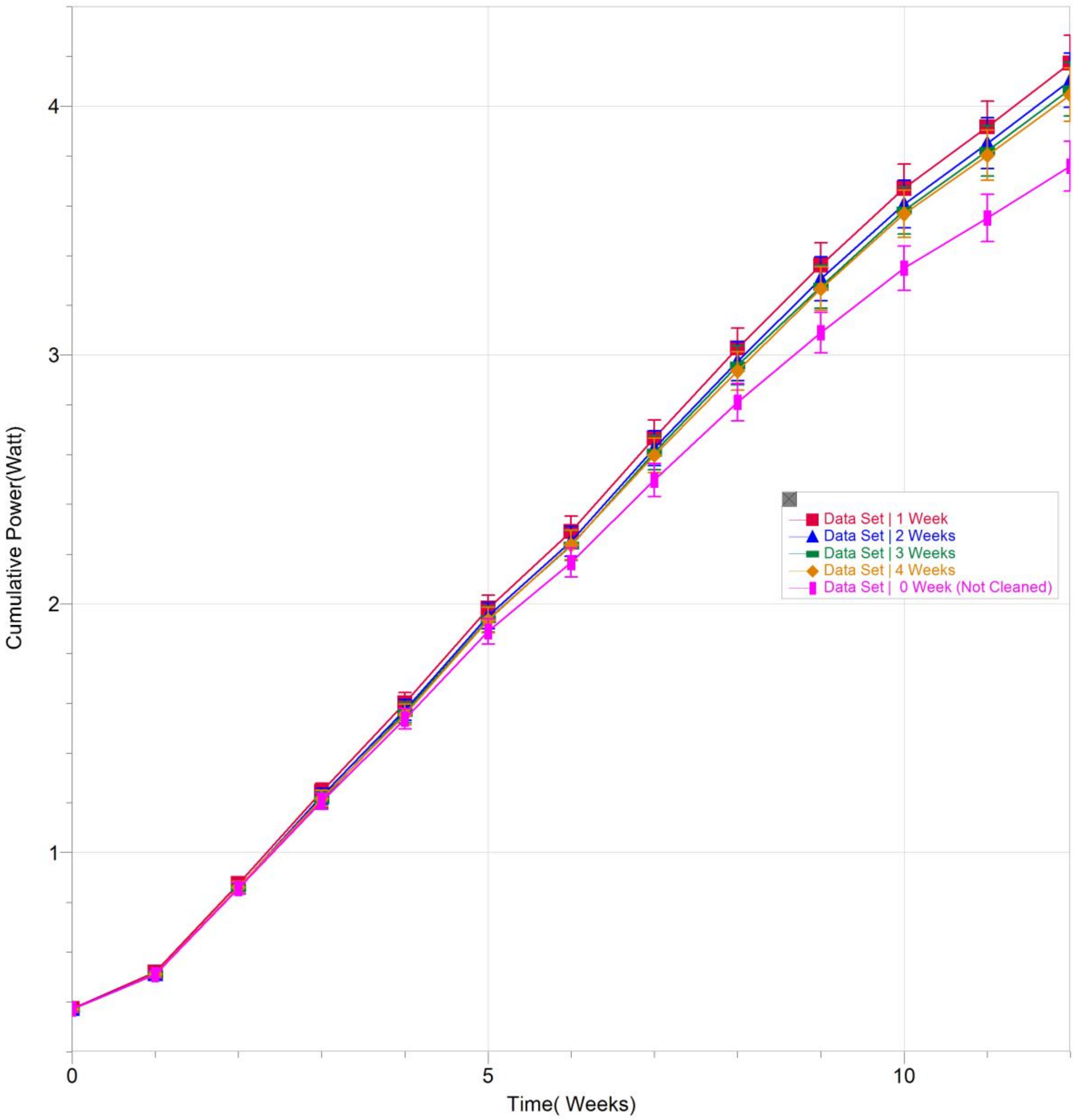
Table 8. Electrical Power Produced by Solar Panels for 12 weeks

In order to observe the cumulative effect of dusting and cleaning, the power outputs of each week were added up to reach the cumulative power output of each panel set at the end of the experiment:

Cumulative Electrical Power (Watt/±5.6%)													
Cleaning Period (weeks)	**Week0**	**Week1**	**Week2**	**Week3**	**Week4**	**Week5**	**Week6**	**Week7**	**Week8**	**Week9**	**Week10**	**Week11**	**Week12**
1 (SET-1)	0,373	0,519	0,875	1,245	1,600	1,982	2,291	2,668	3,029	3,362	3,671	3,918	4,175
2 (SET-2)	0,371	0,512	0,860	1,227	1,573	1,952	2,251	2,625	2,974	3,306	3,606	3,851	4,104
3 (SET-3)	0,370	0,509	0,857	1,213	1,564	1,938	2,234	2,608	2,958	3,274	3,580	3,819	4,067
4 (SET-4)	0,370	0,511	0,861	1,218	1,554	1,935	2,236	2,596	2,935	3,266	3,567	3,803	4,046
0 (SET-5)	0,371	0,511	0,857	1,206	1,538	1,890	2,166	2,498	2,811	3,091	3,350	3,552	3,761

Table 9. Cumulative Electrical Power Produced by Solar Panels for 12 weeks

Since only simple addition is done for cumulative power calculations, the percentage uncertainty is not affected.



Graph 1. Cumulative Electrical Power of Panels Having Different Cleaning Periods

To observe the effect of cleaning period, the percentage power gain of each set is calculated with respect to the uncleaned set (SET-5) using the formula:

$$\%\ Power\ Gain_i = \frac{Cumulative\ Power\ of\ Set_i - Cumulative\ Power\ of\ SET\_5}{Cumulative\ Power\ of SET\_5} x\ 100$$

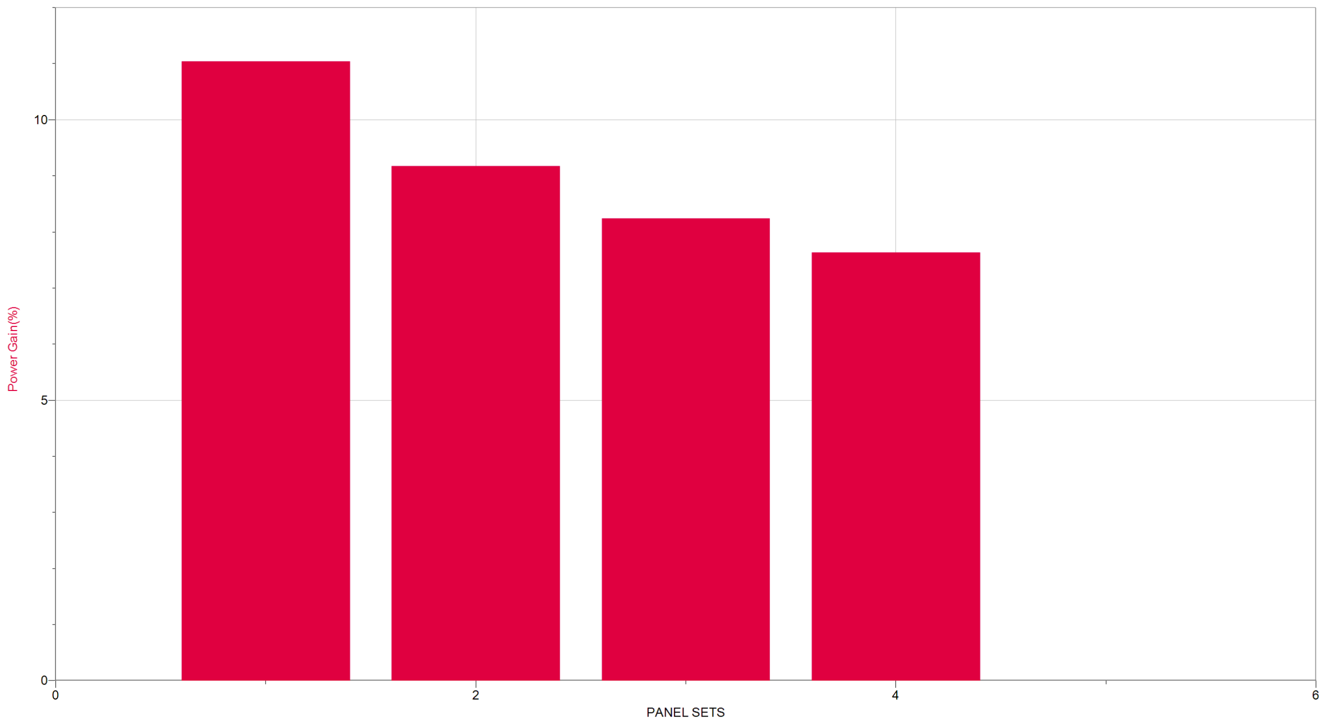
For an example calculation, the % power gain obtained by cleaning the panels every two weeks (SET-2) is:

$$\% \, Power \, Gain = \frac{4.104 - 3.761}{3.761} x \, 100 = 9.1\%$$

Cleaning Period (weeks)	Electrical Power Gain (%)
1 (SET-1)	11.0
2 (SET-2)	9.1
3 (SET-3)	8.1
4 (SET-4)	7.6
0 (SET-5)	-

Table 10. Percentage Electrical Power Gain of Solar Panel Sets

The graph of percentage power gain for panel sets are given below:



Graph 2. Percentage Electrical Power Gain

Results of the Experiment

In this investigation, it was observed that as the dust accumulates on the panels, the power outputs of solar panels decrease, which is seen in Table 8. At the beginning of the experiment (Week 0) when all panels are clean, they produced virtually the same electrical power (0,371 Watts on average). At the end of the experiment, the most frequently cleaned panel(SET-1) produced 0,257 Watts electrical power, whereas the set that is never cleaned(SET-5) produced a mere 0.209 Watts.

There are increases and decreases in the electrical power outputs of the panel sets (Table 8) throughout the experiment. These fluctuations in power values are mainly due to the differences in the cleaning periods. The measurements done a week after the cleaning are higher as expected. But there are some exceptions which are mainly due to insolation difference rising from changing weather conditions. A dramatic power drop at Week 1 is observed for all panels. Therefore it can be concluded that the sky was mostly cloudy and insolation was limited that week.

The average power for never cleaned panel set (SET-5) for the whole experiment duration is calculated (excluding the Week 1) as 0.295 Watts which leads to a power loss of $\frac{(0.371-0.295)}{0.371} * 100 = 20.5\%$ when compared to the average power of clean panels at the beginning of the experiment (0.371 Watts). So, it can be concluded that accumulated and never cleaned dust causes 20.5% decrease on solar panels performance for a period of 12 weeks in Ankara.

When the cumulative power outputs were examined, as seen in Table 9, the never cleaned panel has the lowest power output (3.761 Watts). The most frequently cleaned set has the highest power output (4.175 Watts), and the power output (4.104 Watts, 4.067 Watts and 4.046 Watts for SET-2, SET-3 and SET-4 respectively) decreases as the cleaning period increases. As seen from Graph 1, the difference in the performances becomes recognizable after Week 5. Expectedly, never cleaned panel has a considerably low power output.

With the help of Table 10 and Graph 2, it was observed that cleaning once a month (SET-4), which is the longest period, gave a 7.6% performance improvement over no cleaning at all. The most frequent cleaning (SET-1) yielded the highest performance gain (11%) as expected.

Therefore, the relation between the cleaning frequency of panels and power output was clearly observed. The research question was answered and the hypothesis was supported:

As the cleaning period of the solar panels increases, the electrical power output will decrease due to the dust accumulated on panels. The performance of the panels that are cleaned most frequently will be higher than the ones with longer cleaning periods.

It was also observed from Table 5 that the standard deviation is low and similar for all sets, which shows high reliability and consistency in the experiment. The low percentage error (5.6%) indicates that the experiment is accurate.

Discussion and Evaluation

The findings of this investigation point to the fact that dust accumulation causes considerable performance loss in solar panels and periodic cleaning of the panels is a necessity to improve panel performance. The performance loss of solar panels can reach extreme levels depending on the abundance of dust in a region. [16] [17] There is no general optimum cleaning period

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[16] Micu A. (2019). *Dusty solar panels slash power output by over 35%, study reveales*. ZMEScience. https://www.zmescience.com/ecology/renewable-energy-ecology/solar-panels-dust-output/

[17] Hussain A., Batra A., Pachauri R. (2017). *An experimental study on effect of dust on power loss in solar photovoltaic module.* https://jrenewables.springeropen.com/articles/10.1186/s40807-017-0043-y

mentioned in the literature. Localized optimum cleaning periods can be determined based on the environmental conditions where the panels are installed and the cost of cleaning.[18] [19]

Offering cheap and clean electrical power, solar energy utilization is becoming more and more popular for most of countries in the world, Turkey included. So, the results of this investigation can be useful to anyone who wants to use and implement solar energy.

Strengths	Reason it's believed to be strength
An automated hardware/software measurement method was used.	Data for all panels was collected simultaneously. Thus, weather-related factors were eliminated.
Compact size solar panels were selected.	Since the dimensions of the set-up were reasonable, it was easy to position it in a shadow-free area.
During the experiment period, the amount of dust accumulation was high as construction sites were in abundance in the surrounding area.	As there was more dust present in the area, the effects of cleaning with different periods were observed more clearly.

Limitations	Effect of Limitation on the result of investigation	Suggested improvement
In this investigation, only dust was examined as a pollutant.	Other important sources: the bird dropping and leaves were not considered.	If all possible contamination sources are examined, the performance loss can be investigated more accurately and more efficient solutions can be found.

[18] Özçelik A.E., Güğül G.N., (2020). *Photovoltaic panels: A review of Cleaning Systems.* Renewable Energy Sources Energy Policy and Energy Management Journal, e-ISSN: 2717-9583. https://dergipark.org.tr/en/download/article-file/1215703

[19] Relysm. (n.d.). *Solar Farm Cleaning Costs.* https://www.relysm.com/solar-farm-cleaning-costs/

The experiment was carried out during the summer months when the weather is generally dry and sunny.	The effects of snow and rain could not be observed.	All possible weather conditions should be evaluated to implement more effective cleaning solutions.
Only manual cleaning using a cloth damped with tap water was used.	The effect of different cleaning agents or methods like electrostatic cleaning has not been investigated.	The dust holding capacity of the panels can be reduced with different cleaning agents and techniques.

As a further study, an experiment that covers an entire year can be carried out to examine the effect of different weather conditions such as rain and snow in more detail. The results can be used to calculate seasonal panel performance losses and determine cleaning periods accordingly.

Application

Manual cleaning methods have various limitations including the difficulty of physically accessing the panels, the possibility of damaging the panels while cleaning, and time and labour cost. Instead, automated cleaning techniques using robotic methods and dust sensors can be implemented, especially for larger solar plants. The period of cleaning can be determined automatically to optimize the cleaning process. However, the initial investment required may be too expensive to afford.

Conclusion

An experimental investigation was carried out to understand the effect of dust decomposition and periodic cleaning on the performance of solar panels. The experiment was conducted in an outdoor setup in Ankara for 12 weeks by gathering data automatically from identical panels subject to the same insolation conditions while one set of the panels were left uncleaned whereas the others were cleaned periodically with four different periods. The solar panel performance was modelled as a function of electrical power produced. It was observed that dust accumulation on the panels, by blocking the solar radiation, reduced the output power by 20.5%, which is alarmingly high. Thus, it was proved in this investigation that to avoid performance losses, the solar panels must not be left uncleaned. Although the results may differ according to the characteristics of the region where the panel is installed, it was clearly observed that cleaning significantly increases the performance of solar panels. In this particular experiment, the increase was found to be 11% by cleaning weekly for 12 weeks.

The effects of fossil fuels on Earth are clear as day, and they are running out rapidly. Humanity will soon be forced to switch to alternative energy sources that are environmentally friendly and renewable. We are already starting to see major changes in society such as the increased supply and demand of electric cars and these changes will only become more frequent going forward. As a result, countries and corporations will start investing more and more into renewable sources, with solar energy being at the top of the list. Therefore, it would be logical to expect that production and maintenance costs of solar panels will drop down from their steep price points to more accessible ones. This will enable more and more individuals to generate their electricity in a reliable, clean, quiet, and relatively cheap manner, putting an end to the dependency on power grids.

Conducting dust analysis on a region before installing solar panel systems and determining appropriate cleaning strategies emerges as an essential task to maximize the utilization of solar energy. Moreover, by taking into account the cost of cleaning, optimized panel cleaning solutions can be applied, thus more efficient solar energy projects can be implemented.

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