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Article

Correlation between concentration of particulate matter 2.5 and solar energy production in Brooklyn, NY

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SUMMARY

Many people have started using solar panels in recent years. Switching to renewable energy sources can greatly decrease the amount of carbon emissions that contribute to climate change. One effect of climate change is a rise in wildfires. Smoke from wildfires can be detrimental to human health by increasing the air quality index (AQI). In June 2023, the AQI drastically increased in Brooklyn, New York due to fires in British Columbia from the west to Quebec and Nova Scotia in the east. We hypothesized that particulate matter (PM) 2.5 would negatively affect solar energy production because when the sun's rays are blocked by clouds or smoke, there is usually less solar energy production. Our hypothesis was supported given that during the month of the fires across British Columbia, Quebec, and Nova Scotia, the PM 2.5 concentration had a strong negative correlation to solar energy production ($p = 0.05$). Throughout the rest of the year, the PM 2.5 concentration generally did not have an effect on solar energy production. PM 2.5's positive correlation with solar production was measured against cloud cover and wind speed as benchmarks for a strong and weak negative correlation. Our findings can help determine what factors should be considered when deciding where to install solar panels or to place solar fields. By making renewable energy more effective we hope that more individuals will choose to switch away from carbon fuel sources.

INTRODUCTION

Climate encompasses weather patterns in a certain area or region over an extended period of time. Currently, the global climate is gradually becoming warmer as the years go on due to the greenhouse effect (1). In general, the greenhouse effect helps keep our earth warm so everything does not freeze. Greenhouse gases, which are mainly produced by fossil fuel emissions, trap the sun's heat, slowly raising the temperature here on earth (2). However, if the greenhouse effect is continuously enhanced it can cause a climate crisis. Climate change has already affected humans and the biosphere greatly. For example, carbon dioxide levels have risen 25% since 1958, glaciers are shrinking, the sea level has gone from rising 1.77 mm/year for most of the 20th century to 3.2 mm/year since 1993 and impacted wildlife by destroying their natural habitats (3, 4). One additional visible indicator of climate change is the increase in wildfires in recent years (5). Wildfires are dangerous to humans, with the smoke having serious effects on human health (6). For example, eye and respiratory tract irritation, reduced lung function, bronchitis, exacerbation of asthma and heart failure, and premature death (7). Therefore, it is essential that as a global society we consider other methods of energy production.

The world's main source of electricity generation comes from fossil fuels. In 2020, 80% of our energy was generated by fossil fuels (8). In contrast, solar energy is a renewable energy source. Other renewable energy sources include wind energy, geothermal energy, hydropower, ocean energy, and bioenergy. Solar energy ranks the highest in abundance on Earth. The rate that solar energy hits the earth is about 10,000 times more than humankind consumes energy (9). Solar energy produces low amounts of greenhouse gasses and is therefore much better for the environment (10). Additionally, solar panels don't have any costs besides the initial installation and the required minimal maintenance like keeping them clean and in good physical condition (11). Solar panels work by absorbing electromagnetic radiation from the sun into a photovoltaic (PV) cell. This energy moves responding to an internal electric field in the PV cell causing electricity to flow (12).

However, the primary disadvantage of solar power generation is its unpredictability. Solar energy generation is reliant on how much sunlight reaches the panels, which will vary based on different weather conditions. For example, cloud cover will block the sun from reaching the solar panels. Time of year will also affect how close that part of the earth is to the sun and will therefore affect the sun's intensity and the number of hours the sun is shining. In addition, solar panels will need space or public support to accommodate the installation of solar panels to produce enough energy (11). Keeping in mind the logic behind clouds blocking the sunlight from reaching the solar panels, it can be presumed that particulate matter in the air would also affect the amount of solar energy produced.

On June 7, 2023, wildfires in British Columbia, Quebec, and Nova Scotia caused a plume of smoke to engulf the entire Northeast of the U.S. in a wave of terrible air quality (13). If the burning of fossil fuels as an energy source for electricity continues, it will continue to emit greenhouse gasses and drive climate change. Hence, this issue of wildfire and worsening air quality may pose an ongoing issue. Therefore, it's good to know how the pollutants from wildfires affect solar production, a substitute for fossil fuel energy.

The smoke from wildfires is a combination of different sized pollutants (14). The air quality index (AQI) measures a variety of air pollution including ozone and other particulate matter. These particles float around in our atmosphere, enhancing the greenhouse effect and making our Earth warmer than it

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should be. We focus on particulate matter that has a diameter of 2.5 micrometers or smaller (PM 2.5 concentration), because it is the size of most inhalable pollutants (15). Since the PM 2.5 concentration is likely to be an increasing concern for inhabitants of the Northeast due to climate change-related particulates, this paper will focus on how PM 2.5 concentration affects solar generation in Brooklyn, NY.

Understanding how AQI affects solar production can inform electrical companies on where to install solar panels to be most productive. If solar panels are greatly affected by the air quality, it may be wise to consider where wildfires are likely to occur and refrain from installing solar panels there. An increase in the effectiveness of solar energy can decrease the amount of fossil fuel energy needed which can slow climate change. The effective production of solar energy has the potential to prevent the rise of wildfires which increases air pollution and ultimately may lead to a decrease in the effectiveness of solar energy.

According to solar companies, cloud cover will affect how much energy your solar panel will produce (12). A study was done using a machine learning system that used the predicted cloud cover to estimate solar production on a given day, showing that cloud cover may have a significant effect on solar production (16). Wind speed was used because it has been tested before and has little effect on solar radiation (17). It was used as a negative control. Therefore, for this study, cloud cover and wind speed will be considered for benchmarks to measure the effectiveness of PM 2.5's correlation to solar energy.

One of the factors that determine solar production in Brooklyn is the season (18). In Brooklyn (and the Northern Hemisphere) during the summer months, the Earth is tilted on its axis towards the sun; therefore, there is potential for more energy production. In contrast, during the winter months, the Earth is tilted the other way, resulting in less solar production during those months (19, 20).

Cloud cover is one factor that is known to block sunlight and therefore decrease the amount of solar energy that is produced (21). Logically, it would make sense that PM 2.5 would play a role in blocking the sun from reaching the solar panels and decrease the energy production. Therefore, we hypothesized that the amount of PM 2.5 will have a negative effect on solar energy production. Our hypothesis was supported when tested with a smaller sample size from May 21 - June 14 which included the days with extreme PM 2.5 concentration levels. However, the effect was not significant when the PM 2.5 levels were not so varied and mostly stayed the same. Therefore, we have provided evidence that PM 2.5 will only significantly affect solar energy production when it is highly abundant, providing instruction for proper solar panel installation.

RESULTS

We studied the correlation between the daily average PM 2.5 concentration in the air (ug/m^3) and the daily total solar production (kWh) in Brooklyn, NY between April 8, 2022 and June 14, 2023. The air quality data was taken from the EPA's database (22). The wind speed and cloud cover data were taken from visual crossing's database (23). The solar production data were taken from privately owned home solar panels bought from SunPower (24). To put into context how much the PM 2.5 affected the solar production, the cloud cover and wind speed were also correlated to the daily average solar production (kWh).

Solar Production and Average Temperature

In Brooklyn, NY, temperature is generally a visible indicator of the season. To test how seasons affected solar production, the temperature was correlated to the solar production during the entire year. Generally, the higher the daily temperature the higher the solar production, which consequently suggests that the time of year affects the daily total solar production (p < 0.01, linear regression; **Figure 1**). Due to the effects of the time of year on solar production, the data for the other parameters were split up into four groups corresponding to the different seasons. The data for PM 2.5, cloud cover, and wind speed were then graphed by their season so each season would not have such a great effect on how much solar energy was produced. Even with this correction, the temperature still varied in a range of 20-40 degrees Fahrenheit in any given season. Therefore, the temperature still played a significant role determining the difference in solar production which confounded the significance of the factor that was being measured.

Solar Production and PM 2.5 Concentration

We measured the relationship between the PM 2.5 concentration and the solar production across all four seasons in order to see if PM 2.5 has an impact on solar production. During the months of March through May, there was no correlation between PM 2.5 concentration and solar production (p = 0.74, linear regression; **Figure 2A**). In June through August, September through November, and December through February there was little to no correlation between PM 2.5 concentration and solar production (p = 0.20, 0.35, and 0.42, respectively, linear regression; **Figure 2B-D**).

After finding these results the data was cut up further. The month where the PM 2.5 was highest was isolated so that its effect could be seen clearly. We found a statistically significant negative correlation between PM 2.5 concentration and solar production between May 21 and June 14, 2023 (p = 0.04, linear regression; **Figure 3**). A similar test was done by breaking down the data into similarly small segments, but the segments were from 2022. The segments were from

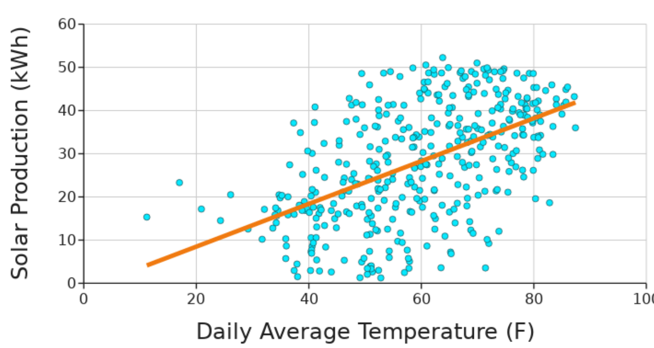

Figure 1: Correlation between daily average temperature and daily total solar production. Linear regression graph shows how temperature is correlated to solar energy production (n = 401). The data shown on the graph starts from April 8, 2022 and goes until June 14, 2023. Linear regression: p < 0.01, r2 = 0.285, equation: y = 0.4951x - 1.409, rho = 0.546.

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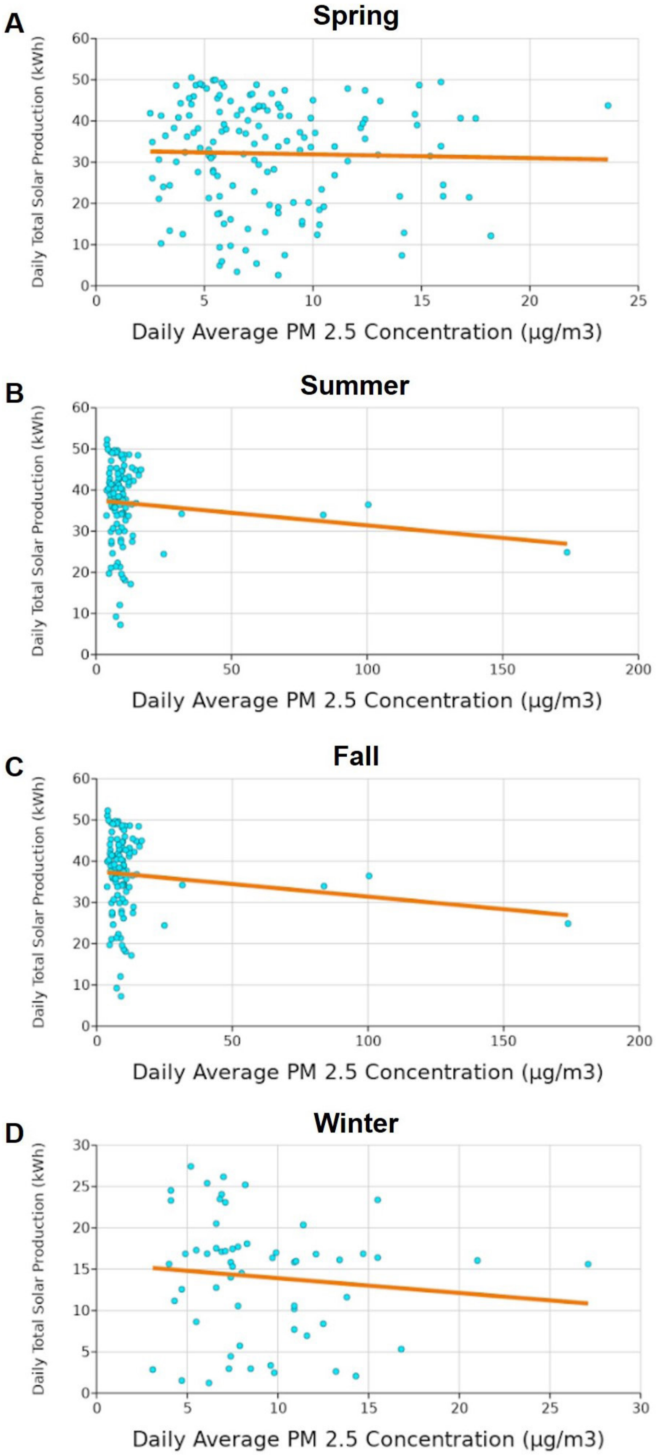

Figure 2: Correlation between daily average PM 2.5 concentration and solar production across four seasons. Linear regression graphs show PM 2.5's correlation to solar energy production. PM 2.5 was compared to solar production by season. A) March through May (Spring) was not significantly correlated. n = 145, p = 0.74, r2 = 0.000755, equation: y = -0.09065x + 32.81, rho = -0.0705. B) June through July (Summer) had minimal evidence of correlation. n = 107, p = 0.20, r2 = 0.0154, equation: y = -0.061x + 37.51, rho = -0.126. C) September through November (Fall) had minimal correlation. n = 91, p = 0.35, r2 = 0.00963, equation: y = -0.3233x + 23.38, rho = -0.136. D) December through January (Winter) had minimal correlation. n = 59, p = 0.42, r2 = 0.0116, equation: y = -0.1718x + 15.7, rho = -0.197.

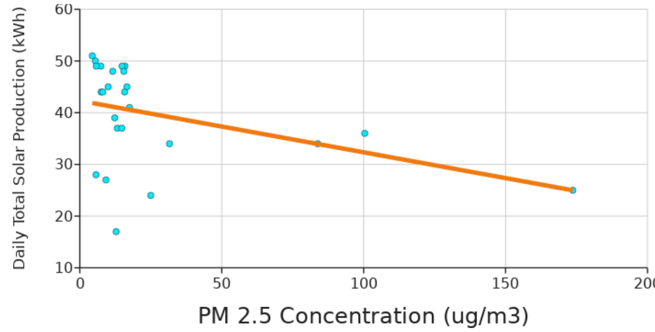

Figure 3: Correlation between PM 2.5 concentration and solar production between May 21 and June 14, 2023. Linear regression graphs show PM 2.5's correlation to solar energy production from May 21, 2023 through June 14, 2023 (n = 25). PM 2.5 data was correlated to solar production data including a spike in PM 2.5 concentration but not diluted with less extreme data points. Linear regression: p = 0.04, r2 = 0.16, equation: y = -0.0997 + 42.31, rho = -0.469.

June 1 - 14, May 1 - 14, and May 15 - 30 (p = 0.86, 0.65, 0.04, respectively, linear regression; **Figure 4**). This shows that when the data was broken up into smaller sample sizes without having high levels of PM 2.5, in general, there was little to no correlation. Therefore, it was not the breakup of the data that caused the strong negative correlation between PM 2.5 and solar energy production in 2023, but the high levels of PM 2.5.

Solar Production and Cloud Cover

The correlation between solar production and cloud cover was tested as a control to see how PM 2.5 affected solar energy production in relation to other factors. The correlation between cloud cover and solar production had a statistically significant negative effect across the months of March through May, June through July, September through November, and December through January ($p < 0.01$, linear regression; **Figure 5A-D**). The strong correlation between solar production and cloud cover shows that cloud cover was one of the main factors that determines how much solar energy is produced.

Solar Production and Wind Speed

We measured the correlation between wind speed and solar production across all four seasons in order to see the impact PM 2.5 had on solar production in relation to windspeed's impact on solar production. In the months of March through May and September through November, there was a statistically significant negative correlation between wind speed and solar production ($p < 0.01$, linear regression; **Figure 6A**, **6C**). In the months of June through August, there was no correlation between wind speed and solar production (p = 0.74, linear regression; **Figure 6B**). In the months of December to February, there was little indication that there is a correlation between wind speed and solar production (p = 0.16, linear regression; **Figure 6D**). It is interesting that in the seasons of spring (March through May) and fall (September through November), which have similarly mild temperatures, there was a strong correlation between wind speed and solar production; while winter (December through February) and summer (June through July), which have more extreme temperatures, p-values were higher, therefore a lower correlation.

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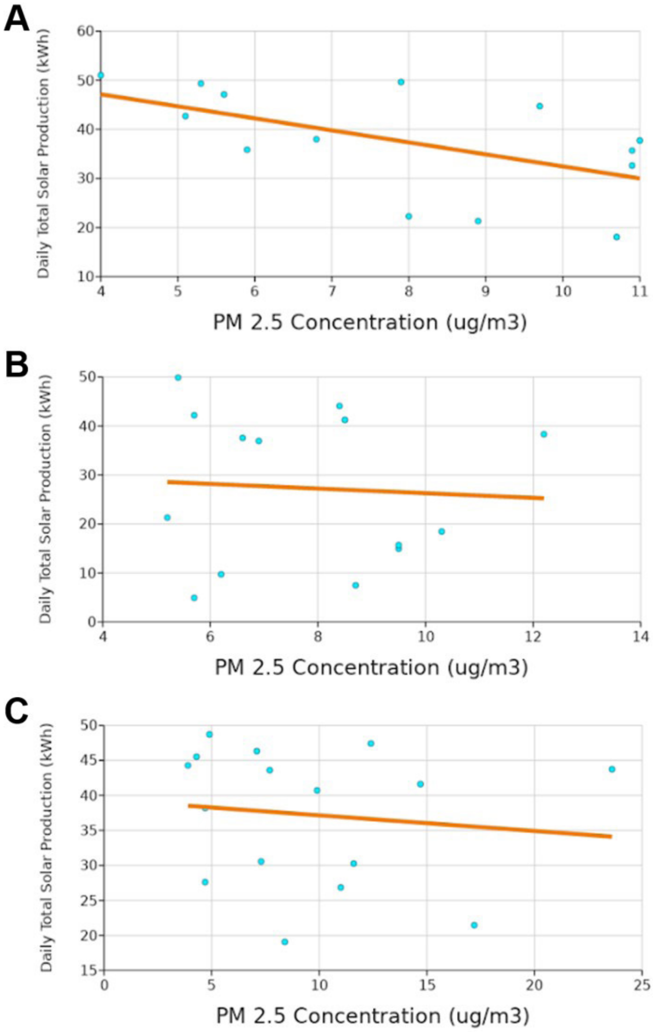

Figure 4: Correlation between PM 2.5 concentration and solar production with a small number of days the year before the fire. Linear regression graphs show PM 2.5's correlation to solar production. A) June 1 through June 14 2022. n = 14, p = 0.82, r2 = 0.00426, equation: y = -0.4748x + 31.02, rho = -0.165. B) May 1 through May 14 2022. n = 14, p = 0.65, r2 = .0155, equation: y = -0.2237x + 39.39, rho = -0.249. C) May 15 through May 30 2022. n = 16, p = 0.04, r2 = 0.394, equation: y = -0.271 + 2068, rho = -0.476.

Wind Speed and Cloud Cover

We measured the correlation between wind speed and cloud cover in order to see whether the reason for wind speed's correlation to solar production was its correlation to cloud cover.

The correlation between daily average wind speed and daily average cloud cover had a statistically significant effect ($p < 0.01$, linear regression; **Figure 7**). The positive correlation between wind speed and cloud cover shows that the most likely reason for the correlation between solar production and wind speed was its correlation to cloud cover.

DISCUSSION

After analyzing the results, we discovered that PM 2.5 has an effect on solar energy production once the data were broken down into smaller groups. This was seen when the data showed a big spike in PM 2.5 concentration in June

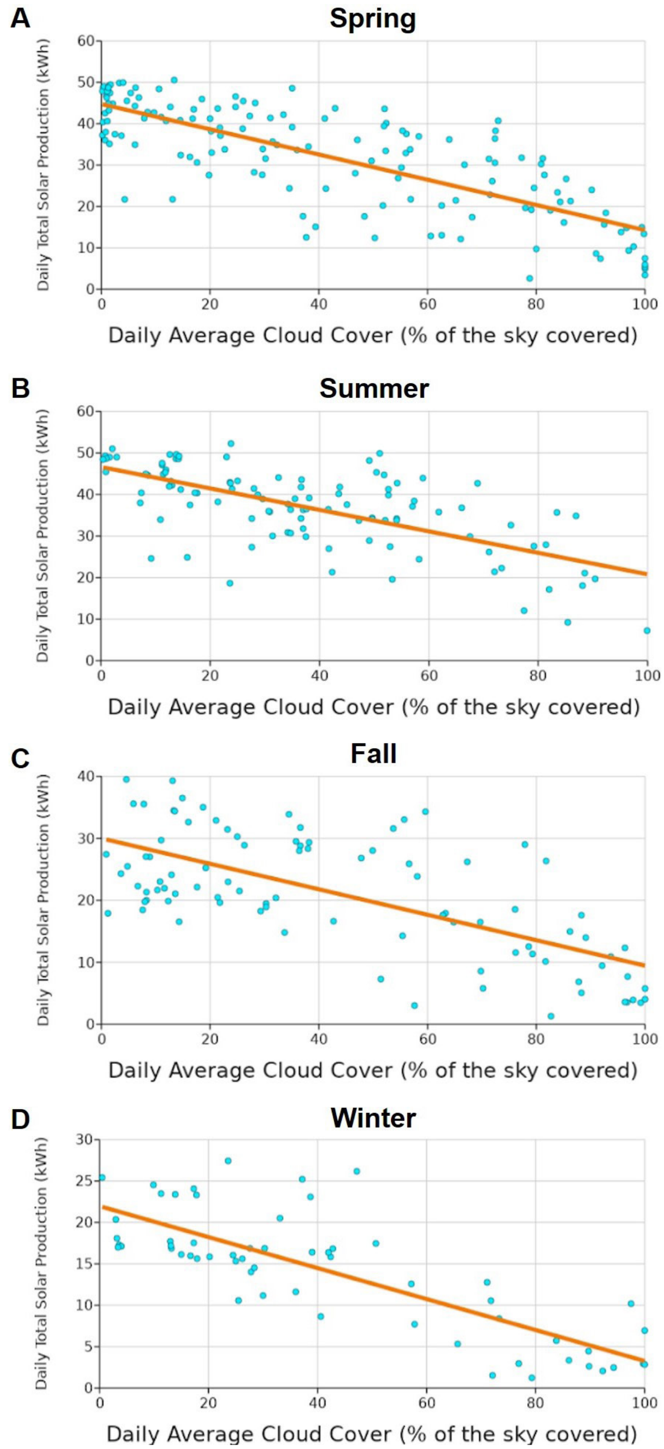

Figure 5: Correlation between daily average cloud cover and solar production across four seasons. Linear regression graphs show cloud cover's correlation to solar energy production. A) March through May (Spring) was strongly negatively correlated. n = 145, p < 0.01, r2 = 0.611, equation: y = -0.3049x + 44.76, rho = -0.771. B) June through August (Summer) was strongly negatively correlated. n = 107, p < 0.01, r2 = 0.438, equation: y = -0.2584x + 46.63, rho = -0.625. C) September through November (Fall) was strongly negatively correlated. n = 91, p < 0.01, r2 = 0.452, equation: y = -0.2055x + 30, rho = -0.61. D) December through February (Winter) was strongly negatively correlated. n = 59, p < 0.01, r2 = 0.636, equation: y = -0.187x + 21.97, rho = -0.761.

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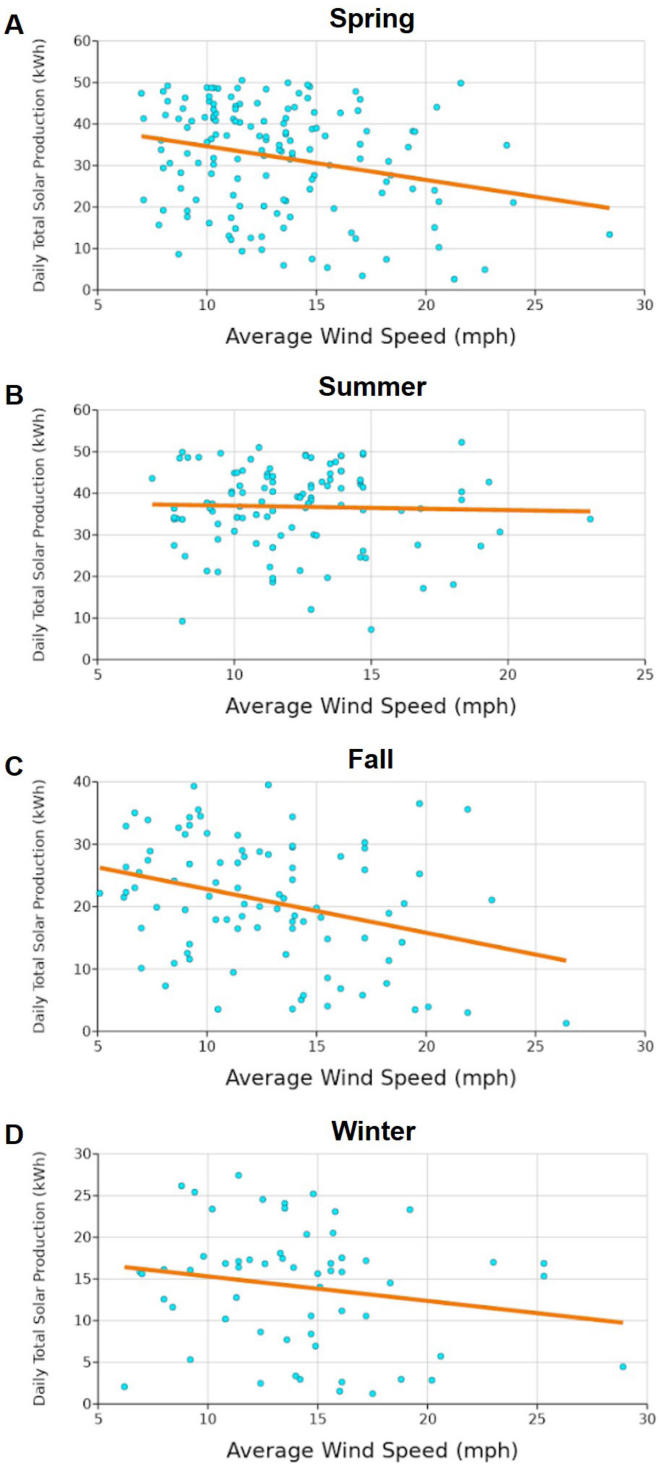

Figure 6: Correlation between daily average wind speed and solar production across four seasons. Linear regression graphs show wind speed's correlation to solar energy production. A) March through May (spring) was strongly correlated. n = 145, $p < 0.01$, r2 = 0.0635, equation: y = -0.8093x + 42.73, rho = -0.202. B) July through August (Summer) was not correlated. n = 107, p = 0.74, r2 = 0.00108, equation: y = -0.105x + 38.05, rho = 0.0279. C) September through November (Fall) had a strong negative correlation. n = 91, $p < 0.01$, r2 = 0.101, equation: y = -0.699x + 29.79, rho = -0.293. D) December through February (Winter) might be correlated. n = 59, p = 0.16, r2 = 0.0351, equation: y = -0.2941x + 18.25, rho = -0.186.

2023 ($p = 0.04$, linear regression; **Figure 3**). But, there was no definite correlation shown when the data was analyzed in bigger chunks.

While our study contained many important controls, there were ultimately unavoidable challenges that confounded our data. One of the challenges with this study was that the PM 2.5 concentration did not vary greatly. It generally stayed under 50 ug/m3 and went into the 100s about three times during the wildfires. Therefore, correlation with excessive PM 2.5 concentration was only able to be studied during the month of the fire. While the study would have been more significant with more data points with extreme levels of PM 2.5 concentration, the prevalence of lower PM 2.5 levels is likely more environmentally relevant. Another limiting factor was the air quality data. Air quality was by far the hardest data to find and was missing data points, contained doubles of some specific dates, and changed stations throughout the time period that was being analyzed. There was no data for May 31, 2022 and the entire month of January 2023. The air quality was reported in Brooklyn by three different stations, but each station did not provide a report every day. Some days had a single datapoint, two data points, or three data points. To manage the data, it was sorted by station and then put together from different stations to get an almost complete set of data (excluding May 31, 2022 and January 2023). Additionally, the solar production data was taken from one set of solar panels. The data analysis would have been more robust if more sets of solar panels were involved in the analysis.

After analyzing the results, PM 2.5 concentration does not appear to be a major factor in determining how much solar energy will be produced when there is generally a low concentration of PM 2.5 in Brooklyn, NY. A factor that does make a big impact in how much solar energy is produced is cloud cover and time of year. An effective place to install solar panels would be a sunny area near the equator, for example, Brazil, Ecuador, Indonesia, etc. In addition, these places would not be affected by the Earth's tilt and always be close to the sun (25). In theory, those less populated hot places can supply energy for more populated places that get less sun radiation, like New York City. If PM 2.5 starts polluting the air more and more reaching levels of 100 ug/m3 and higher, it may become a factor limiting the solar energy production. In that event, PM 2.5 levels would be extremely important to start watching and taking into consideration in relation to solar panels. Other causes of drastic spikes in PM 2.5 concentration could be due to weather patterns that trap carbon emissions and drastic changes in traffic volume (26). Our results were similar to the results of a study done in India, China, and the Arabian Peninsula. They found that the dust (PM) in the air affected solar panel energy production in 2017 (27). In the future, factors that affect solar production can be further pursued by testing other pollutants in the air that are not PM 2.5 to understand which may have greater effects on solar energy production. Further research on higher levels of PM 2.5 should be done by researching what would happen if the PM 2.5 level rose even higher.

While totally stopping pollution is impossible, if every person in the world chose to walk instead of riding in a car there would be significantly less pollution in the atmosphere. Although some people choosing to walk some of the time instead of riding in a car would not immediately cause the

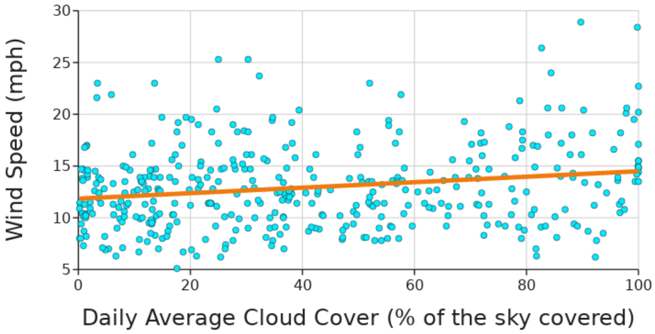

Figure 7: Correlation between daily average cloud cover and daily average wind speed throughout the year. Linear regression graphs show cloud cover's correlation to wind speed (n = 401). Cloud cover data was correlated to solar production data. The results were $p < 0.01$, r2 = 0.0403, equation: $y = 1.522x + 21.61$, rho = 0.175.

greenhouse effect to stop raising the temperature of the Earth, it could mitigate the greenhouse effect which can in theory prevent wildfires which cause spikes in PM 2.5. This will not only continue the vicious cycle of pollution but lower solar panel production levels.

MATERIALS AND METHODS

The solar energy production was measured by one set of solar panels in a private home in Brooklyn, NY in kWh. The average PM 2.5 concentration in Kings County (Brooklyn, NY) was measured against solar energy produced. The PM 2.5 concentration indicated the amount of air pollution. The Environmental Protection Agency (EPA) measures the air quality by the PM 2.5 that is inhalable and is smaller than 2.5 micrometers (PM 2.5). The particles were measured in ug/m3 (24). Other factors that were taken into consideration were cloud cover, wind speed, and time of year. Cloud cover was measured in percentage of the sky that was covered by clouds. Wind speed was measured in miles per hour. Temperature was the proxy for time of year measured in Fahrenheit.

First, the temperature was graphed in a linear regression against the solar production from the whole year. Since temperature is a proxy for time of year, this will show whether time of year has an effect on solar production.

The remaining three factors were split up in groups of three months: March through May, June through August, September through November, and December through February representing spring, summer, fall, and winter, respectively. These groups of months were used as sections to split up the data so that the data was measured against data from the same time of year. All of these factors (excluding temperature) mentioned above were graphed in relation to the solar energy produced in a specific set of months to show their effect on solar energy production in a linear regression.

The air quality data were taken from the EPA's database (22). The cloud cover and wind speed data were taken from the visual crossing database (23). The solar data were from a database from one set of home solar panels bought from SunPower. SunPower provides the data of how many kWh were produced daily in a downloadable spreadsheet (28). Most of the data collected was not missing any data points except for the EPA's air quality data. The air quality data was missing May 31, 2022 and the month of January 2023, which made it necessary to skip over that data during the analysis. In addition, the data had many dates with double or triple PM 2.5 concentration daily averages because of the different stations that were providing data. Therefore, the data had to be sorted by station and be pieced together with a combination of different stations so that there was only one value for the Daily Average PM 2.5 concentration each day.

All the data was stored and organized on google sheets. The data was imported, graphed, and analyzed on Data Classroom.

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