# Energy and Economic Losses due to Soiling on Utility Scale PV Systems to Guide Timing of Cost Effective Cleaning

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**Acknowledgements**

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***PROPOSAL***

## Chapter 1 – Abstract

The purpose of this senior project is to develop and recommend a cleaning schedule for Goldtree Solar Farm that is both economically beneficial and an efficient use of cleaning for the client. Solar farms can have various factors that influence the cleaning schedule such as weather behavior, time of the year, soiling, and other factors. Through this senior project, the goal is to assess these factors effect on the solar farm to produce a cleaning schedule that will maximize energy production, maximize profits, and prevent insignificant cleaning

This analysis is motivated by defining and promoting the benefits of regular maintenance of PV systems for the financial and power production gains. The conclusions and results of this research will be reported to and shared with REC Solar, to recommend a cleaning and maintenance schedule that best benefits both them and Cal Poly.

## Chapter 2 - Introduction

As global warming continues to become an urgent crisis, utilizing renewable resources for energy production has become a prominent topic in moving away from fossil fuels and pollution. Solar farms are one way of producing renewable energy along with a minimum carbon footprint. With the use of this energy production also comes with some disadvantages. Photovoltaic cell energy production is affected by its cleanliness and can have a large effect on its efficiency. Soiling from dirt, debris, pollen, and more does affect solar farm energy production therefore reducing the profitability of this energy source [1][2]. To avoid this issue, farmers attempt to clean their solar panels, however this is a costly expense and can be ineffective if the cleaning schedule is not regulated [3][4].

For these reasons, this project intends to identify and quantify a cleaning schedule that would maximize energy production along with minimizing cost to boost profits. Data will be gathered from the Cal Poly Goldtree solar farm regarding energy production, and this data will be analyzed to draw conclusions about energy and financial losses due to soiling and environmental conditions [5][6]. Currently, industry costs for cleaning a solar farm range from $0.50-$1.00 per module. This would equate to a range of $8000-$16,000 to clean the Goldtree solar farm. With an irregular cleaning schedule, this cost can add up and decrease the profit margin. By analyzing natural occurring weather events and debris collected on these panels, this project will be able to develop a cleaning schedule that best caters to the location along with decreasing unnecessary cleaning dates.

Ultimately, this project aims to expand beyond the Goldtree solar farm. The end product should be a program where a solar farm owner can input data specialized to their farm's location, such as precipitation, energy production history, and other weather events. The program will be able to inform the user about the best time to clean their farm. Different solar farms have very different soiling types, and therefore different cleaning needs, so this project will need to account for these differences [ 7].

Soiling on solar modules is not as simple as a thin layer of dust that can be brushed away. Frequently the soiling consists of different types of dirt, pollen, and animal byproducts [8]. Additionally, dew, fog, and light rain can cause soiling to turn to mud and stick to modules more firmly, requiring more vigorous cleaning. For some farms and some soiling levels, simply a heavy rain will clean the modules sufficiently, but sometimes soiling will build up too much for rain to wash it away. This project seeks to show when real cleaning is necessary.

## Chapter 3 - Customer Needs, Requirements, and Specifications

### 3.1 Customer Needs Assessment

Solar farm designers and owners need to know when and how often to clean their sites for producing the best economical decision. While energy production directly after cleaning can be significantly higher than before cleaning, it may not stay higher long enough to be worth the cost of cleaning frequently. It is known that REC Solar spends thousands of dollars each time they have the Cal Poly Solar Farm cleaned, but they are unsure if it is worth it to clean multiple times per year. Additionally, weather events at different points of the year may make cleaning more or less necessary, so site designers and owners need to know when it is most advantageous to clean their sites.

More specifically, REC solar would like to be able to input their past energy production and the weather forecast and know whether it's more advantageous to clean their solar farm in the next couple of days or wait a few weeks. To do this, a rate of soiling must be created so that losses per day can be quantified: both monetarily and in amount of energy.

The Californian Clean Energy and Pollution Reduction Act -SB 350 requires the reduction of greenhouse gas emissions to 40 percent below 1990 levels by 2030. Increasing the energy production of solar farms is an essential part of reaching this goal, which adds on to the necessity of this research to help define and report the most effective cleaning times for maximum energy production.

### 3.2 Requirements and Specifications

These companies want to minimize the expenses on cleaning the sites, especially since in this case Cal Poly doesn't pay anything for cleaning. From an engineering perspective determining the effects of cleaning the PV system truly is for energy production, and therefore economic benefit. Data will be used to recommend a cleaning schedule for REC Solar so that they can spend as little money as possible and still get benefits from cleaning.

Both consumers and solar farm owners want the site to produce as much energy as possible. Cleaning the site regularly can improve this, so the factors which impact this the most will be determined via different experimental methods. All parties want to maximize energy produced because it will produce more money, and bring the company closer to meeting government sustainability requirements.

Solar farm owners want to see how soiling actually impacts energy production. Therefore, an analysis of any correlation between various soiling levels, and how much energy is produced shall be produced and defined. This requirement is important because if moderate to heavy soiling doesn't produce much less energy than a clean panel, it means owners can wait longer to clean the site. However, if energy production drops vastly with moderate soiling, it will be worth it to clean more frequently.

The production of energy also correlates to the time of year which is a concern for solar farm operators. All four seasons bring different weather environments such as rain, wind, sunrises, misting, and more. By identifying the behaviors of the PV system at different times of the year, solar farm designers could benefit by identifying how energy production is affected at different times. This correlation will be viewed during the winter and early spring period.

With the cleaning process requiring water, solar farmers also do not want to be wasteful when an upcoming rain is approaching. With an unmonitored cleaning rotation, farmers can spend thousands on cleaning only to have the panels cleaned again soon after by the rain. By observing the weather behavior, the lifespan of a clean and when to not clean during the rainy season will be determined.

**TABLE 1: Energy and Economic Losses due to Soiling on Utility Scale PV Systems Requirements and Specifications.**

| Marketing Requirements | Engineering Specifications | Justification |
|---|---|---|
| 1, 2, 3 | Quantify impact of cleaning on energy production | Cleaning is expensive, and REC Solar wants to clean only when it will increase profits and energy production |
| 1, 2, 3, 4 | Analyze energy production using data from a Solmetric PV analyzer - comparing with multiple other parameters | Maximizing the energy production of the PV system provides more sustainable energy to be used and sold to which provides a larger profit |
| 2, 3 | Examine the correlation between energy production and soiling at varying levels of soiling | If energy production is massively different at higher soiling levels, it will show that the site owners should clean more often. If not, it will show it isn't worth the money to clean frequently |
| 1, 2, 3, 4 | Survey the energy production throughout Summer, Fall, and early Winter to see correlation between time of year, and energy production | If soiling levels are lower during Fall and Winter due to rain, or if energy production levels are lower in general, it will be less worth it to clean in winter months |
| 1, 2, 3, 4, 5 | Recognize weather related precipitation and how to incorporate it with regular cleaning schedule | Minimizing the amount of water used when cleaning is beneficial and would lose money if cleaned during a rainy period |
| 1, 2, 3 | Determine the point at which cleaning on that specific day saves more money in energy production than it costs to clean the modules | Concrete, numerical justification is necessary to adequately decide whether to clean on any given day |

**Marketing Requirements**

1. Minimize cleaning expenses
2. Maximize production of energy
3. Cleaning scheduled as needed
4. Recognize the effect of time of year on energy production
5. Weather's impact on cleaning schedule

**TABLE 2: Energy and Economic Losses due to Soiling on Utility Scale PV Systems Deliverables**

| Delivery Date | Deliverable Description |
|---|---|
| 1-21-20 | Requirements and Specifications V1 |
| 1-28-20 | Block Diagram |
| 2-4-20 | Literature Report |
| 2-11-20 | Cost Estimates |
| 2-11-20 | Gantt Chart |
| 2-18-19 | ABET Sr. Project Analysis |
| 2-25-20 | Requirements and Specs V2 + intro |
| 2-29-20 | Report V1 |
| 1-30-20 | EE 461 Design Review |

## Chapter 4 - Functional Decomposition

### Functional Decomposition

Figure 1 shows the Level 0 Block diagram of this project. There are three main inputs: history of cleaning of the site and specific inverters, history of energy production on each inverter, and history of precipitation. These three factors will be used to create a soiling rate, which in turn will show how much money and energy is lost each day that the site is not cleaned. A fourth input, weather forecast, will show the likelihood of rain (and thus, a light cleaning), in the near future. These combined results will predict the best time to clean the solar farm. These are also outlined in Table III, along with the system's overall functionality.

### 4.1 Level 0

**Table 3: Functional Decomposition of Photovoltaic System Analysis**

| **Module** | **Photovoltaic System Analysis** |
|---|---|
| Inputs | • Past Precipitation Data<br>• Past Energy Production Data<br>• Site Cleaning History<br>• Weather Forecast |
| Outputs | • Recommended Cleaning Schedule<br>• Money Saved by cleaning when recommended |
| Functionality | • The Photovoltaic system will be analyzed to identify whether cleaning in the next few days would be more cost effective than waiting to clean. This analysis method should be transferrable between solar farms. |

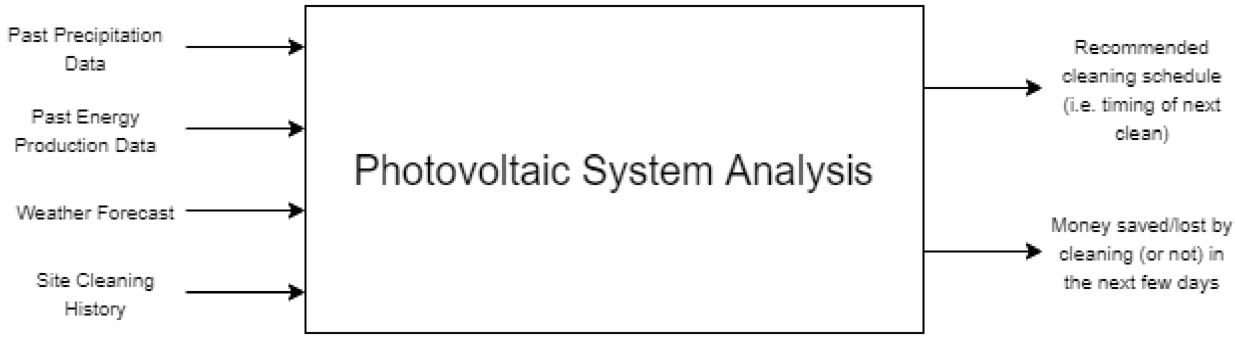



**Figure 1: Level 0 Block Diagram**

### 4.2 Level 1

The Level 1 Block Diagram, seen in Figure 2, illustrates the internal steps taken to determine a cleaning schedule and recommendation. The three data history inputs precipitation, energy production, and site cleaning will be graphed to show a ratio of energy production between a clean and increasingly dirty string of modules. This graph should have a roughly linear slope, resetting when precipitation or cleaning occurs. These data sets will be used to create a baseline soiling rate for that specific farm, and from there a rate of money lost. The weather forecast data will show if it will rain soon. If the soiling rate indicates the farm is currently dirty, and no rain is predicted for the next few weeks, the program will show that the site should be cleaned very soon. If the farm is clean, or a heavy rain is predicted in the near future, it will be unnecessary to clean soon. The program will also show the amount of money the site owners should make by cleaning when recommended.

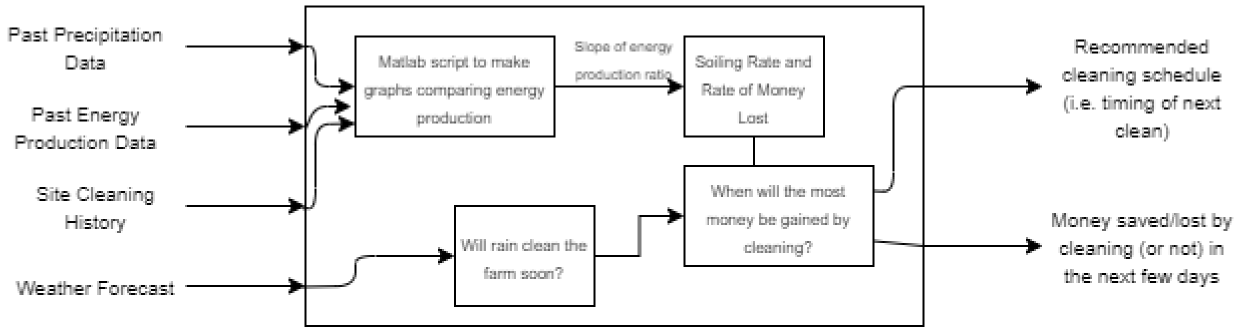



**Figure 2: Level 1 Block Diagram**

## Chapter 5 -Project Planning

### 5.1 Cost Estimates

This project is a fairly low-cost project, when the costs of labor are not included. The costs are outlined in Table IV. The primary cost is the cost of transportation to the Goldtree solar farm to clean one inverter every other week. The costs of water, squeegee, and other cleaning supplies are not paid for by the project team, and the inverter and its data collection device are already a part of the solar farm. The only other cost is labor, both cleaning the panels and the time spent analyzing data and creating the program. This labor cost is not an actual cost of the project, because the project team is receiving school credit

**Table 4: Cost Estimates for Photovoltaic System Analysis**

| Item | Justification | Cost | Quantity | Total |
|---|---|---|---|---|
| Gasoline | The PV solar farm is located off of Highway 1 near California's Men's Colony. To clean the solar panels, transportation will be needed. | $4.09/ gallon | 15 Round trip => 5 gallons | $20.45 |
| Water | To clean the panels, water will be the main natural resource used to shower and wash the arrays. Water will be provided for the project making it a paid expense | N/A | N/A | N/A |
| Squeegee | Along with water, the panels will be cleaned with a squeegee to wipe panels and remove debris. Squeegee will be provided for the project making it a paid expense | N/A | N/A | N/A |
| Solmetric PVA-1000S PV Analyzer | To measure energy production, the Solmetric device will be used to identify these trends. The Solmetric equipment will be provided for the project making it a paid expense | N/A | 1 | N/A |
| Manual Labor | Participants of this project will contribute their time and labor to clean panels. | $5 a panel | 1500 panels | $7,500 |
| Total: | | | | $7,520.45 |

### 5.2 Gantt Charts

The figures below outline the timeline for this project. Figure 3 shows the tasks expected to be completed in Fall Quarter, 2019. During this time, the project plan was developed piece by piece. Peer, instructor, and advisor feedback was received at each stage, and changes and updates were made. The end result of this quarter was a comprehensive plan for the project, including block diagrams, specifications and requirements, a timeline, and economic and ethical analysis. This plan will be ever evolving throughout the remaining two quarters, but the first quarter of careful planning was imperative.

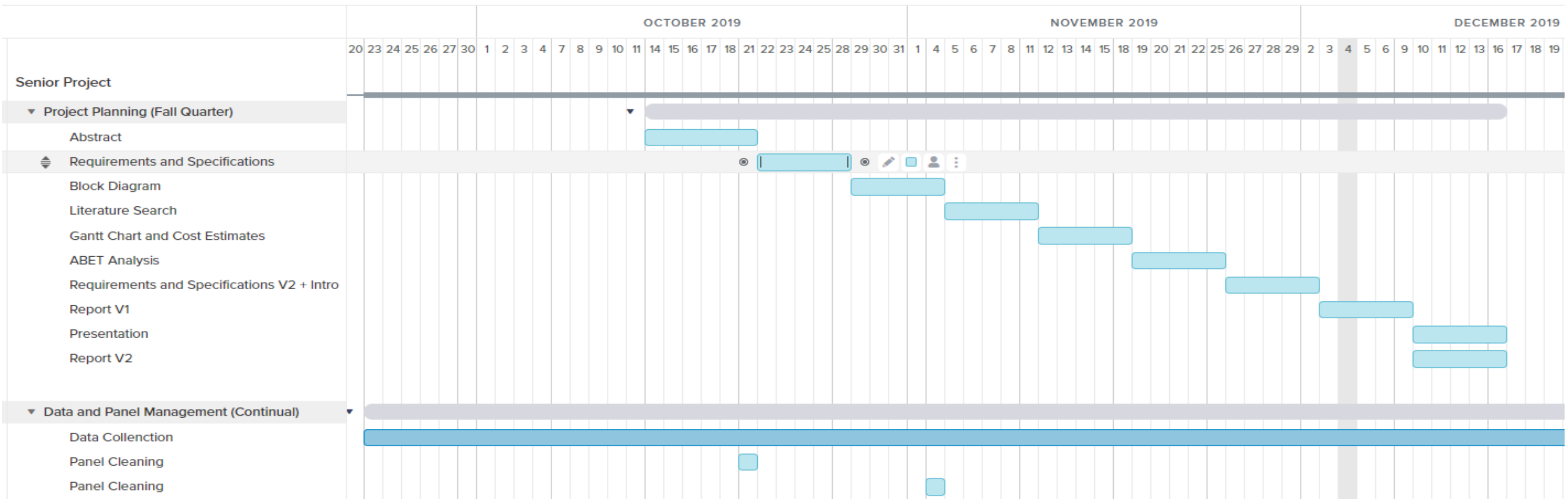



**Figure 3: Gantt Chart Fall 2019**

Figure 4 outlines the tasks to be completed in the Winter Quarter, 2020. This includes multiple iterations of the analysis design process. Initially this included observed trends in the solar farm, created multiple approaches to a soiling rate, and redefined the exact purpose of the project. Regular meetings with the advisor, Dale Dolan, were critical to the progress made in this quarter.

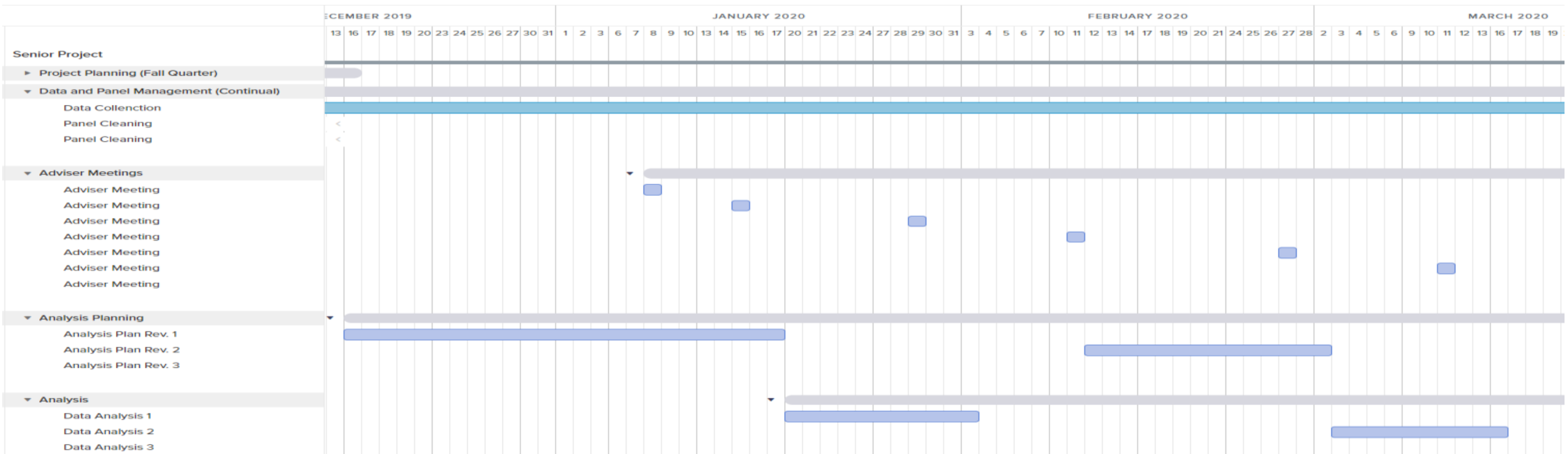



**Figure 4: Gantt Chart Winter 2020**

Figure 5 shows the tasks planned for Spring Quarter, 2020, including the final cycle of analysis planning, with regular meetings with advisor. After this, a comprehensive recommendation for REC Solar will be created, that could be used for other solar farms if they input their own data. The last three weeks are reserved for finalizing this report and presentation, as well as some buffer time.

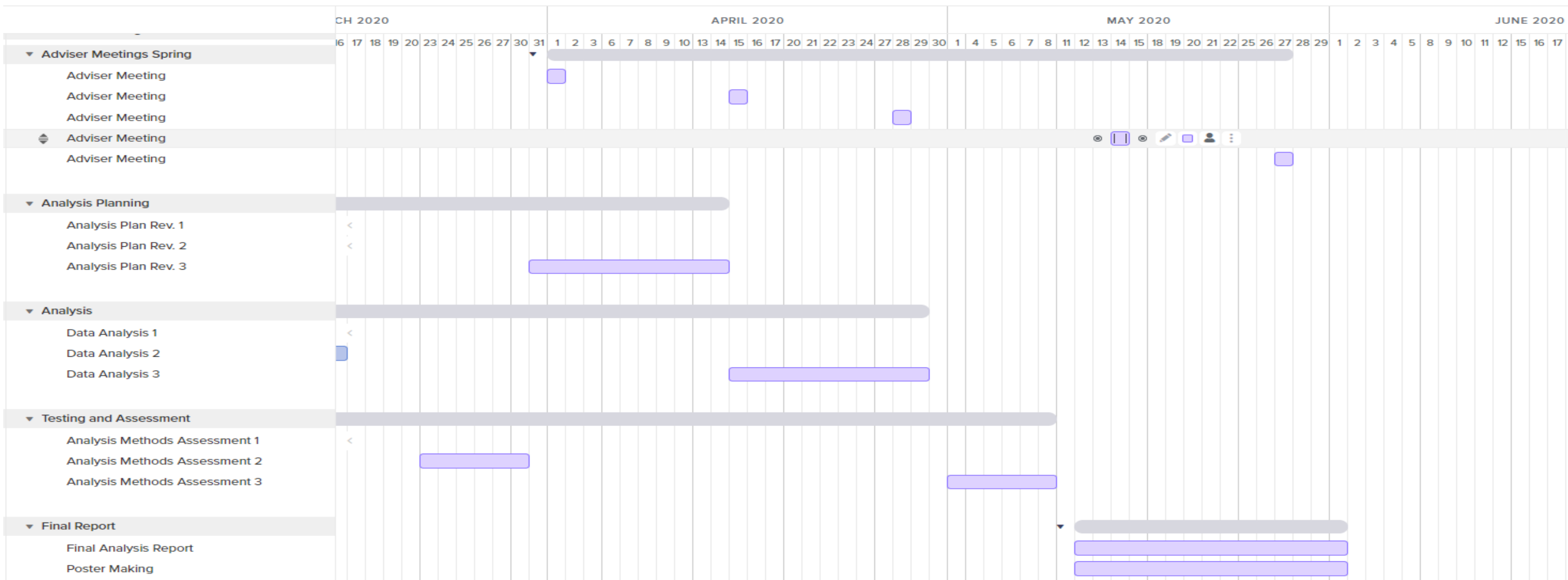



**Figure 5: Gantt Chart Spring 2020**

***Development and Design***

## Chapter 6 – Goldtree Solar Farm

Goldtree Solar Farm is located off highway 1, north of San Luis Obispo next to California's Men Colony. This 4.5-MegaWatt solar plant is owned by REC Solar and has a power purchase agreement with Cal Poly to provide power to the university's campus. This Solar Farm will be vital to the development of this project as the data and modules from this site will be used to develop the solutions to creating a more cost-effective guide for cleaning times. REC Solar will be able to provide information through their portal, https://web3.greenpowermonitor.com/application/login, which will provide all the necessary points for the trial of this project.

## Chapter 7 – Required Data

The purpose of this proposal is intended for Goldtree Solar Farm, but ideally this proposition will be applicable at different solar sites with differences such as weather, size, and more. Outlining what inputs from assorted solar farms customers is an important factor to help develop an algorithm that is applicable anywhere. Figure 6 displays the necessary data needed from clients along with the purpose of that specific data in creating a solution for a client.

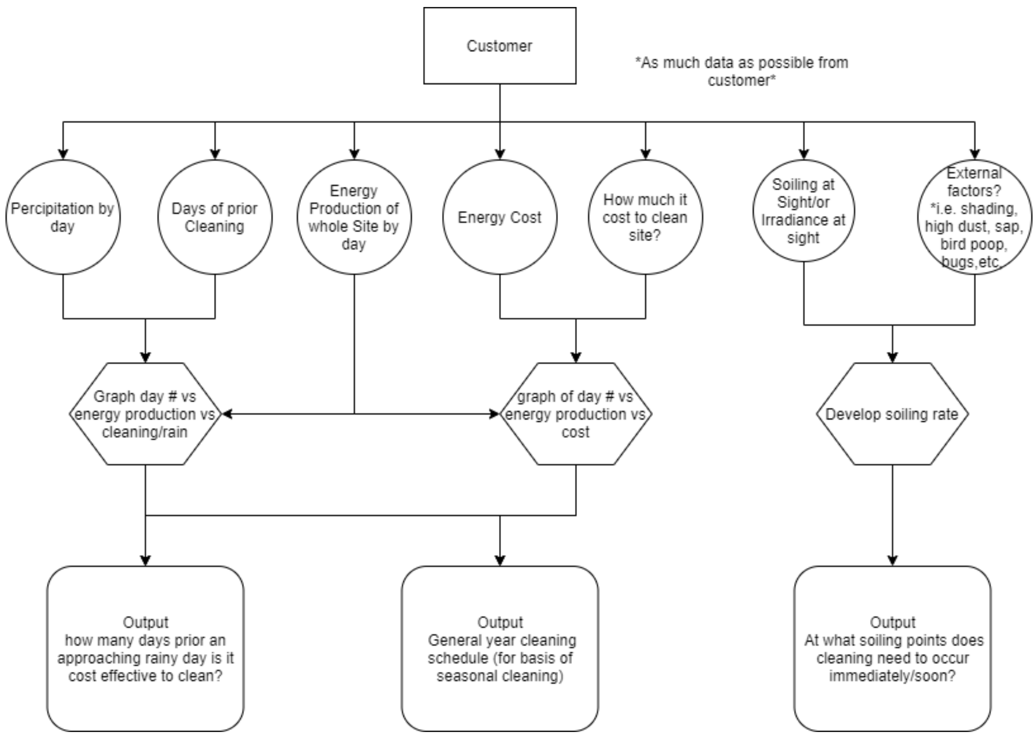



**Figure 6: Customer Inputs to Outputs Flowchart**

### 7.1 Precipitation and Prior Cleaning

The intention of the precipitation and cleaning dates is to help analyze the change of product of production. Evidently, when solar panels are heavily soiled or dirty, the energy produced by modules is not at its maximum performance until they are cleaned whether through a contractor or rain. This data is important because it will help define how much more energy is produced after the panels are cleansed. Previous cleaning dates were provided by Professor Dolan.

**7.2 Soiling and External Factors**

Determining the effects of dirt, dust, and other extraneous grime will be used in creating the soiling rate of a solar farm. The intent of a soiling rate is to certify how quickly an array of panels gets dusty. As well external factors are a way of encompassing site-specific problems that may contribute to the soiling rate due to the farm's location such as above average air pollution, pollen, or animal fecal activity. For Goldtree Solar Farm, soiling stations will be providing the data of the daily soiling cumulative value through the ARES Soiling measurement station. Figure 7 demonstrates the average soiling rate from both stations over the time of June 1, 2019 to April 17, 2020. From these graphs, identify the soiling rate was terminated by averaging all positive slopes over large time periods as shown in figure 8. This concluded that the soiling rate is equivalent to 0.09815.

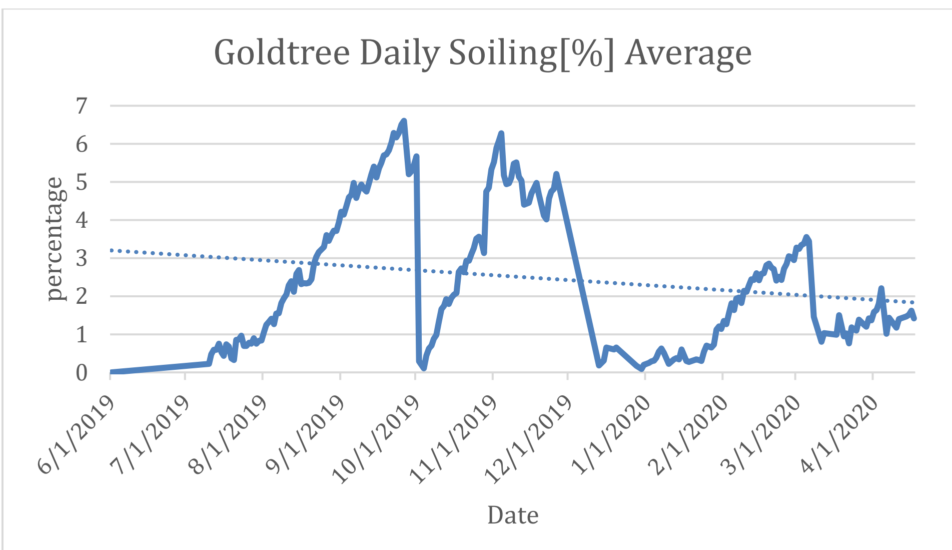
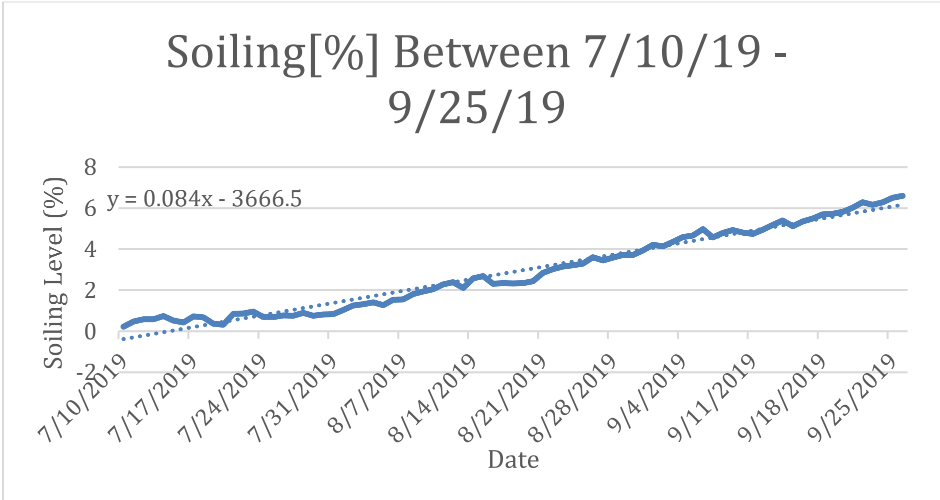
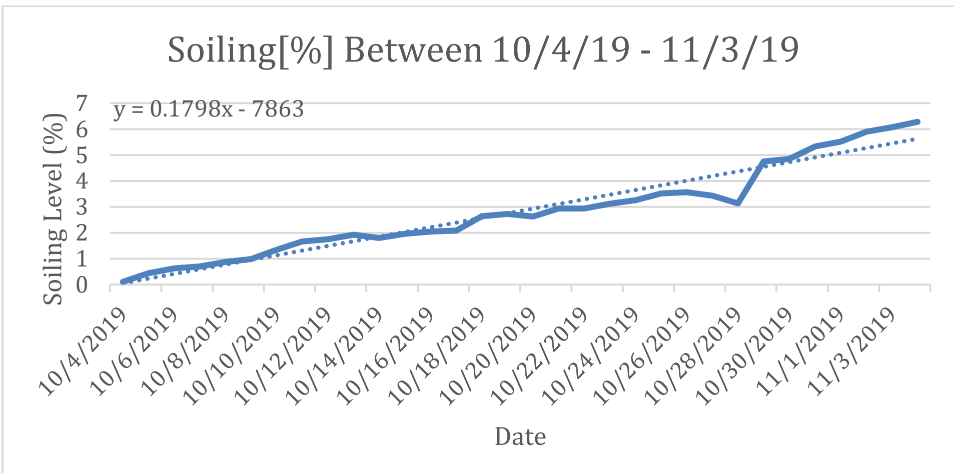



**Figure 7: Daily Soiling Percentages**



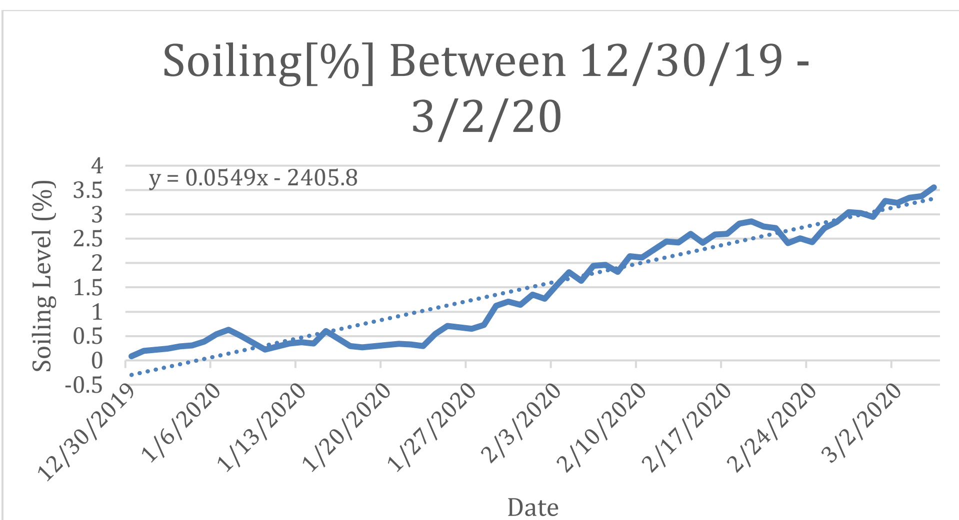




**Figure 8: Incremental Soiling Percentages Over Various Periods**

### 7.3 Cost and Maintenance

An important factor in developing an efficient and cost-effective cleaning schedule is the finances of maintaining the site along with profits that come from it. Cleaning the farm should not occur when the cost of maintenance outweighs the profits that come with cleaning the modules. To clean the entirety of Goldtree Solar Farm would cost between $8,000 and $16,000. For this analysis, the target cost is $16,000, and it will be assumed that the revenue generated is $0.06 per kilowatt hour of energy produced.

### 7.4 Site Energy Production

Goldtree Solar Farm is expected to produce 4.5 Megawatts and generate over 11,000,000 kWh per year [9]. The energy production of Goldtree Solar Farm or any solar site is an important detail for making a cost and time effective cleaning schedule because this information can be used to gauge if a farm is reaching its peak performance, or how inefficient the site is. Using other variables given by clients, the site energy production can be used to help determine the effect soiling and scale the effect of dusty panels has on the expected production of energy.

## Chapter 8 – Data Interpretation

### 8.1 Data Management

With the fundamental data being provided by the client, it is essential to regulate all given information to create interpretable information with thorough organization. The given data for Goldtree Solar Farm was standardized by several aspects including the date, the day number for the year, and the day number from this project's reference frame. Doing so helps make the data more straightforward to decipher as it allows the several sets of inputs to be in the same standpoint for developing graphical reports. Statistics were all placed on Excel sheets to be utilized by MATLAB for developing an algorithm. Figure 9 shows an example of the data management of the data in Excel.

| Date | Day # in relative timeline | Day # in tradiotional Sun days | Precipitation(mm) |
|---|---|---|---|
| 11/25/2019 | 178 | 329 | 0 |
| 11/26/2019 | 179 | 330 | 0 |
| 11/27/2019 | 180 | 331 | 1.32 |
| 11/28/2019 | 181 | 332 | 13.68 |
| 11/29/2019 | 182 | 333 | 6.2 |
| 11/30/2019 | 183 | 334 | 0.6 |
| 12/1/2019 | 184 | 335 | 8.2 |
| 12/2/2019 | 185 | 336 | 2.6 |
| 12/3/2019 | 186 | 337 | 0.4 |
| 12/4/2019 | 187 | 338 | 3.12 |
| 12/5/2019 | 188 | 339 | 10.28 |
| 12/6/2019 | 189 | 340 | 0 |
| 12/7/2019 | 190 | 341 | 0 |
| 12/8/2019 | 191 | 342 | 1.88 |
| 12/9/2019 | 192 | 343 | 6.92 |
| 12/10/2019 | 193 | 344 | 0 |
| 12/11/2019 | 194 | 345 | 0 |

| Date | Day # in relative timeline | Day # in tradiotional Sun days | Goldentree #1 Soiling[%] | Goldentree #2 Soiling[%] | Average |
|---|---|---|---|---|---|
| 3/6/2020 | 280 | 66 | 3.78 | 3.1 | 3.44 |
| 3/8/2020 | 282 | 68 | 1.5 | 1.42 | 1.46 |
| 3/9/2020 | 283 | 69 | 1.34 | 1.14 | 1.24 |
| 3/11/2020 | 285 | 71 | 0.94 | 0.67 | 0.805 |
| 3/12/2020 | 286 | 72 | 1.06 | 1 | 1.03 |
| 3/17/2020 | 291 | 77 | 1.09 | 0.88 | 0.985 |
| 3/18/2020 | 292 | 78 | 1.54 | 1.47 | 1.505 |
| 3/20/2020 | 294 | 80 | 1.08 | 0.81 | 0.945 |
| 3/21/2020 | 295 | 81 | 1.2 | 0.84 | 1.02 |
| 3/22/2020 | 296 | 82 | 0.94 | 0.59 | 0.765 |
| 3/23/2020 | 297 | 83 | 1.36 | 1.01 | 1.185 |
| 3/24/2020 | 298 | 84 | 1.35 | 0.92 | 1.135 |

**Figure 9: Data Management Examples**

### 8.2 Algorithm Development

The first step of development was to determine the output of the algorithm. Since the project aims to show when it is monetarily worth it to clean the solar site, the output must center on some amount of money. This is called the `target`. The `target` can be changed, and it is currently set to equal the amount of money it costs to clean the site. Because of the unpredictability of rain, which cleans the panels, rain cannot impact the output. Rain is more common in the winter months, so naturally it does not make sense to clean the site if rain is expected within a certain period of time. This leads to the question: How many days do we need without rain, for the cleaning to be worth the money? That question led to the output days without rain (`DWR`).

Next, inputs were determined. A comparison would need to be made between energy production if the site was cleaned `today`, and energy production if the site was *not* cleaned `today`. A .csv file containing energy production of the entire site each day of 2019 was read, and the variable `cleaned_energy` was created as an array of daily energy production. This array was fed into a segment of code that shifts the index of the array by the `today` variable. This means that the first value of the array is the energy theoretically produced by a cleaned site today, and the following 364 values in the array are for the proceeding year. This created the variable `cleaned_energy2`.

Finally, a segment of code was created to determine the number of days needed without rain, after cleaning, to make back the money spent on cleaning. A variable called `money_made` was the indicator of how much money was made due to cleaning `today`. To determine the excess money made, it was necessary to the energy produced if the site was not cleaned `today`. In theory, the site was cleaned sometime before today, and thus a variable `days_since_clean` would represent the number of days since the last clean if the site was not cleaned `today`. A variable `d` was iterated each pass through the while loop, and represented the days since `today`. Using the soiling rate developed above, a variable `soiled_energy` was created. The formula for this was:

```
soiled_energy_d = (1 - (0.0009815 * days_since_clean))*cleaned_energy2(d);
```

The amount of money made on day d was then calculated using the following formula:

```
money_made = money_made + (cleaned_energy2(d) - soiled_energy_d) * price_kwh;
```

The variable price_kwh represents the money the company makes per kilowatt-hour. The while loop runs until `money_made` is equal to or greater than the `target` value, which is typically the amount of money it costs to clean the site but can be set to a higher value if the company chooses it wants a higher target amount of money.

The `d` value the while loop ends on is the number of days without rain needed for the cleaning to be worth the price. This value is output to the command line as the variable `DWR`.

***Results and Performance***

## Chapter 9 – Outcomes

### 9.1 General Year Cleaning Schedule

The results have shown that it is worth the money to clean the site once per year, between June $1^{st}$ and July $1^{st}$.

The data in rows 1-4 shown in Table 5 below shows a model of a year where the site is cleaned four times, beginning in April. The average number of days between cleans is 90 days; however, that number will become larger in the winter months due to increased rain and decreased energy production. The November cleaning is unnecessary because it is right before the rainy season, and the data shows that there would need to be 121 rain-less days for the site to be worth cleaning at this time. It is unreasonable to expect 121 rain-less days after November, so the site would not be worth cleaning at that time. Additionally, the March $11^{th}$ cleaning can be presumed unnecessary because there will certainly be rain between the last clean (August $18^{th}$) and March, and it is likely to rain at least once more after March $11^{th}$. The August $18^{th}$ cleaning is also likely to be unnecessary because 84 days without rain brings us to November $10^{th}$, and it is unlikely the site would not see a heavy rain during October and early November.

Rows 6-9 in Table 5 show dates of last clean based on a theoretical last day of rain. In the area of California this site is based, there is little to no rain between April or May and September or October. The theoretical last rain was set to May $1^{st}$, and if the site was cleaned on June $1^{st}$ it would need 99 days without rain for the clean to be worth the money. This means that if there is no heavy rain until September $8^{th}$, the site will be worth cleaning. This is very probable in this geographical location. As seen in row 7, if the site were to be cleaned on June $1^{st}$ and then September $8^{th}$, it would need 83 more days without rain to be worth cleaning. This is extremely unlikely, so a second clean would probably not be reasonable.

Row 8 shows the site receiving rain on May 1st, and then being cleaned on July 1st. This shows 81 rain-less days before the site makes the cleaning money back, which is September 20th. This is also fairly likely in this location, but slightly less likely. A second clean on September 20th also shows to be unreasonable, because 111 days without rain after September 20th is very unlikely.

Row 10 shows the site receiving rain on May 1st and being cleaned on August 1st. The result is 71 days without rain until the site makes the money back, which is October 11th. It is fairly likely the site will receive rain before October 11th, making this cleaning schedule unreasonable.

The final date tested was cleaning on May 2nd, the day after the theoretical rain. This date was tested because it appeared to be more reasonable to clean closer to the last date of rain. The result was 125 days without rain required to make the target amount of money. This is September 4th. This cleaning schedule is not as recommended as cleaning on June 1st or July 1st, because in the location modeled there is some chance of rain during the month of May. Postponing cleaning until June or July heavily reduces the chance of rain post-cleaning. If the site were cleaned on May 2nd and rain occurred during May, it would render the clean worthless.

**Table 5: Year-Long Cleaning Schedule**

| | Last Clean or Rain | | Today | | |
|---|---|---|---|---|---|
| Row # | Day # | Date | Day # | Date | DWR |
| 1 | 91 | April 1 | 152 | June 1 | 77 |
| 2 | 152 | June 1 | 230 | August 18 | 84 |
| 3 | 230 | August 18 | 314 | November 10 | 121 |
| 4 | 230 | August 18 | 70 | March 11 | 41 |
| 5 | | | | | |
| 6 | 121 | May 1 | 152 | June 1 | 99 |
| 7 | 152 | June 1 | 251 | September 8 | 83 |
| 8 | 121 | May 1 | 182 | July 1 | 81 |
| 9 | 182 | July 1 | 263 | September 20 | 111 |
| 10 | 121 | May 1 | 213 | August 1 | 71 |
| 11 | 121 | May 1 | 122 | May 2 | 125 |

### 9.2 Forecasting Cleaning Dates

The primary purpose of this model is to analyze whether a clean is viable on a certain day. This is done by putting the day number of the last clean into the `last_clean` variable, and the day of the theorized day of the next clean into the `today` variable. This is possible even if the last clean was in the previous year. The only limitation for dates is if the projected clean date is over one year past the last clean, the program will assume the two dates were in the same year.

## Chapter 10 – Conclusions

### 10.1 Limitations

The primary limitation is that this model only returns one type of output: the number of days without rain until the target amount of money is made back. There is currently no way to analyze the amount of money made per day, which could be useful when deciding between two very similar cleaning dates. The only metric when deciding when to clean is how soon rain is predicted to occur, which is very uncertain.

Additionally, the model does not perform soiling rate analysis. The rate was developed externally and is unique to the site analyzed in this project. If this model were to be optimized for commercial use, it would need to have an input for previous soiling rate data. Ideally a .csv file with daily soiling rates over multiple years could be input, and used rather than a steady increase per day.

### 10.2 Errors and Uncertainties

One thing that could create errors in the output of the model is the averaged soiling rate. The soiling rate used was very general, and a rate more specific to each day would create a more accurate result. Additionally, weather events such as fog or cloud cover may negatively impact the energy production, leading to more days required without rain than the model predicts, before the money is made back. Another uncertainty relates to the type of soiling. While soiling accumulation is distinguishable, some external factors that contribute are harder to establish such as air pollution, pollen, and tougher debris that stick to the panel. With this incertitude, this project concluded that these external factors will either be recognized by the soiling meter, or make only a small insignificant difference, that the external factor can be ignored. Finally, another uncertainty that came with this project is the predictability of rain. Precipitation is not a variable that can be anticipated and relying on years past rain pattern provides some knowledge but still no certainty over the behavior of upcoming weather for a year. California for example had been in a drought from 2011 to 2018 but has been out of that state over these recent years.

**10.3 Improvements**

This project could be improved in multiple ways. The first is a more explicit soiling rate. The current soiling rate was determined using soiling meters, which are a fairly accurate way of getting soiling rate. However, we averaged the rate over a period of time, leading to a very generalized soiling rate. This could have been more accurate if soiling data had been collected every day for multiple years, and the years were averaged for each day. Then, each day could have had a specific soiling rate rather than an average one for the whole year.

The second is a more accurate baseline for cleaned site energy production. Since the data used was from one year's worth of daily energy production, and the site was not cleaned every day, inevitably the site was soiled to some extent on most days of that year. Therefore, the data used to represent a theoretical cleaned site energy production was probably too low, and the difference in energy production between clean and soiled would be further increased in reality. This could be slightly improved by averaging multiple years' worth of daily energy production. It could be greatly improved by cleaning the site every day for a year, but that is financially impractical. The final improvement is considering weather. Ideally, multiple years' worth of rain data could be assembled and used to predict whether cleaning in the winter months is ever worth it. One experiment to determine effectiveness of a moderate rain showed that the rain cleaned the surface of the modules just as well as water and a squeegee during a manual clean. This experiment could be repeated and done under more controlled conditions for a more confident result.

**10.4 Final Verdict**

This project shows that the site should be cleaned no more than once per year, sometime between June 1st and July 1st. This is due to the rainy season boundaries. A clean roughly a month after the last heavy rain yields the most reasonable number of days without rain before the money is made back. A second clean at the end of the summer proved to be unreasonable, due to the large number of days without rain required to make the money back.

To determine the earliest date when it would be worth it to clean, input the last clean into the `today` variable and the clean or heavy rain before that into the `last_clean` variable. If the site is cleaned today, to determine the next earliest date it would be worth it to clean, input today's day number in the `today` variable and the day of the last clean into the `last_clean` variable.

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## APPENDIX A — ANALYSIS OF SENIOR PROJECT DESIGN

### 1. Summary of Functional Requirements

The project will be capable of showing a correlation between the soiling, energy production, and efficiency of a PV system. The intention is to guide system owners to update their cleaning schedule based on these correlations.

### 2. Primary Constraints

Difficulties associated with the project involve the prediction of natural weather events and their impact on cleaning schedules, quantifying the amount of soiling, irregular soiling (e.g. pollen, insects, animal byproducts, etc), and inconsistent soiling throughout the site.

### 3. Economic

The cleaning of PV systems provides occupation for individuals in maintenance as well as monetary benefits for system owners. By ensuring the sites are cleaned often enough to create significant energy benefits, they produce more energy from renewable resources, preserving natural resources. Costs from cleaning will be a constant during the duration of operating Goldtree Solar farm, which this project hopes to decrease this expense by updating its cleaning schedule. Benefits from cleaning on a more efficient schedule accrue after the completion of the project and a cleaning schedule has been recommended. The project does not have many costs. The only cost will be the natural resource of water used to clean the site. The project could earn between a few thousand dollars and tens of thousands of dollars. REC Solar will be the main beneficiaries of profit, but Cal Poly will benefit from buying more energy from the farm.

Cost estimates included under **Cost Estimates**

The results of the proposals will be available at the beginning of June 2020. The results will stay accurate for as long as no large weather changes occur. Maintenance will be continuous on the PV system in order to continue to keep the panels clean and efficient. After the project ends, REC Solar will take our recommendations into account when planning their cleaning schedule. Future

Senior Project groups may continue the data collection and analysis to create a more comprehensive recommendation.

**4. If manufactured on a commercial basis:**

This project will be able to take in data from any solar farm, and create a recommended cleaning schedule. If manufactured on a commercial basis, labor costs would need to be considered. Therefore, software would need to be sold for roughly $75-100 to make a profit. This is due to a cost of around $7500 for creation, and a very low number of companies who would actually buy the product. There are very few companies which own solar farms, so they likely wouldn't purchase many licenses, so each one must be expensive.

**5. Environmental**

The natural resources utilized in this affair include water for the cleaning process along with the sun being used for the production of energy with the solar panels. The outcomes of this analysis will help improve the usage of water for cleaning and improve the efficiency of energy production from the sun. The improved energy production will decrease the amount of non-renewable energy needed, therefore reducing Cal Poly's carbon footprint. Long term, cleaning on a more regular schedule will save a lot of water, leaving that water for the use of the environment. It could also prevent use of water during the dry months, helping improve draught. The Cal Poly Goldtree Solar farm takes up a large area of land which affects natural wildlife in the area that would occupy the land as its habitat. However, the field also serves as a feeding resource for local goats owned by farmers.

**6. Manufacturability**

This project could eventually become a software service to analyze data from a particular solar farm and recommend a cleaning schedule based on that. The software would use data similar to what the project will be acquiring: energy production over a long period of time, including multiple cleanings. The users could connect the software to the device which collects data, and the software would perform analysis on the data to create a cleaning schedule tailored to that farm.

## 7. Sustainability

Challenges with maintaining the completed project include changing weather patterns over multiple years, potential changes in nearby landscape such as construction or new trees planted. These things would affect the amount and types of soiling, changing the correlations between energy production, soiling, time of year, and economic losses. This project will increase energy production at this solar site, which decreases the amount of non-renewable resources used to produce energy. It will also ensure that water is only used for cleaning when it will actually have a large impact.

This project would be more effective and sustainable if it was done over multiple years. The main challenge for this would be getting students to work on it for multiple years. Currently, it is a Senior Project, so it only lasts for one school year.

## 8. Ethical

The main ethical implication of this project is related to the recommendation and conclusion regarding a cleaning schedule. From the IEEE Code of Ethics, Article 3 (to be honest and realistic in stating claims or estimates based on available data) is particularly relevant because most of the project is centered around analyzing data and drawing conclusions based on it. It is important that all conclusions and recommendations aren't based on false or altered data, and accurately represent the data. The project must also take into account Article 7, pertaining to fixing errors and properly crediting contributions because the plan and execution of the project will be overseen by an advisor who will give criticism and assist when needed. The data and conclusions could be misused if REC Solar decided to clean (or not clean) according to the recommended schedule, even if doing so would compromise public safety (e.g. a fire threatened the area and REC Solar wanted to clean anyways, or they cleaned during a severe water shortage). This aspect pertains to Article 1 of the IEEE Code of Ethics.

From a Utilitarian framework, the use of some water to clean the solar panels would have negative utility, but the overall increased production would have a larger positive impact on the environment. This, combined with the money saved, leads to a conclusion of a positive net utility.

From the standpoint of Psychological Egoism, the main motivation of the solar farm owners is to make more money because humans generally act in self-interest. However, as a society we want more renewable energy because it will allow us to continue our energy-consumer lifestyle without harming the environment as much, and incentivizing these large companies with money will help us achieve this.

**9. Health and Safety**

This project can have safety concerns for individuals involved in the cleaning process including sunburns, exhaustion, and transportation risks (road accidents). Renewable energy sources will be utilized for this project which helps reduce carbon emissions and air pollution, therefore, improving air quality and respiration.

**10. Social and Political**

One political issue with the project is the use of water to clean solar panels: many argue that using water to clean solar farms is counterproductive to the goal of preserving natural resources, and therefore the farms should not be cleaned if they have to use water. The project impacts REC Solar, who pays for the farm to be cleaned, and Cal Poly, who pays REC Solar for the energy produced. Cal Poly and REC Solar are both direct stakeholders, and the project benefits them by saving money on cleaning and increasing the energy produced. The stakeholders do not benefit or pay equally: REC Solar pays much more because they pay for cleaning, and they are likely to benefit more because this project will save them money on cleaning while getting them more money from Cal Poly. The project does not create any new inequalities.

**11. Development**

The new skills and techniques used during the duration of this analysis include the proper cleaning techniques of solar panels, operation of Solmetric PVA-1000S PV Analyzer, and the use of direct measurements of the solar arrays.

Other skills developed include MATLAB and Microsoft Excel techniques. This project requires heavy use of MATLAB to create plots of energy, including reading data from a .csv file.

# APPENDIX B – MATLAB CODE

```
%% USER INPUTS:
target = 16000;      % target amount of money to be made back
price_kwh = 0.06;    % amount of money received per kilowatt-hour of energy
produced

file_path = 'C:\Users\Sophia\Desktop\Goldtree-Energy by Day-2019.csv';  %path
of .csv file for baseline energy data

last_clean = 314;    %day number site was last cleaned
today = 70;          %theoretical day number site will be cleaned

%% .csv read
length_test=csvread(file_path,1,0);
temp_dsd=size(length_test)-[1,0];
row_num=temp_dsd(1);
length_test=1;
end_row=row_num+1;
vtdp=csvread(file_path,1,0,[1 0 end_row 6]);

cleaned_energy = vtdp(1:(row_num +1), 7);

%% Calculate energy of clean and not cleaned

day = [1:1:365];

for n = 1:365
    if (n < (365 - today+1)) || (n == (365-today+1))
        cleaned_energy2(n) = cleaned_energy(n+today -1);
    else
        cleaned_energy2(n) = cleaned_energy(n-(365-today)-1);
    end
end

%% Determine how many days without rain until money is made back

money_made = 0;
d = 1;
while (money_made < target)
    if (today > last_clean)
        days_since_clean = d + (today - last_clean);     %if we don't clean
today
    else
        days_since_clean = d + (365 - last_clean) + today;
    end
    soiled_energy_d = (1 - (0.0009815 *
days_since_clean))*cleaned_energy2(d);
    money_made = money_made + (cleaned_energy2(d) - soiled_energy_d) *
price_kwh;
    d = d + 1;
end

DWR = d    %days without rain until money is made back
```