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

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TABLE OF CONTENTS

TABLES AND FIGURES

TABLES

FIGURES

Acknowledgments

We would like to thank Dr. Dale Dolan for his guidance and support throughout the duration of this project. He provided tons of information, feedback and insight to help our project develop. We also appreciate his commitment to cleaning solar panels with us and for us in the early morning, we couldn't have completed this project without him.

Thank you to REC Solar for allowing students to run experiments at the Gold Tree Solar Farm and access their inverter production data. This provided the backbone of our project.

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Abstract

The energy and associated economic losses due to soiling on both residential and utility scale PV (photovoltaic) systems can be both significant and avoidable. Losses from 1.2% up to 6% have been reported, which is of interest to system operators [1]. Modules may be cleaned to reduce losses, but this comes with an offsetting economic cost. A quantification of energy losses, and the corresponding economic loss, will allow a determination of a closer to optimal cleaning schedule depending on the level of soiling and corresponding energy loss. Two methods are proposed and compared. Method 1 uses an ARES Soiling Measurement Station to perform irradiance and short circuit current measurements to calculate a soiling rate [2]. Method 2 uses direct measurement of energy production from recorded inverter data. A soiling rate will be determined by measuring energy production in control modules and modules with varying levels of soiling. This data was used to create a program to estimate the profitability of cleaning the PV installation at any given time.

Chapter 1: Introduction

Solar photovoltaic cells produce energy by converting light into electric potential at efficiencies of around 15%-20% [3]. Factors such as composition, temperature, and shading all have an effect on the efficiency of the panel. The goal of this project is to make a recommendation based on a particular kind of shading called soiling. Soiling refers to the shading of solar panels due to dust and dirt that accumulate over time. Without regular cleaning, the efficiency of the panel will drop as dirt and debris accumulate and sunlight has a harder time reaching the panels. Losses as high as 6% have been reported due to soiling [1]. While a 6% drop in efficiency may not seem significant, it can mean losses of hundreds of thousands of kWh on a large solar farm.

In areas such as the Middle East or Africa, soiling has a large impact on the efficiency due to the amount of dust in the air as well as lack of rainfall. These are the areas in which the effect of soiling on panels is well researched. In the figure below, dust intensity is shown throughout the world:

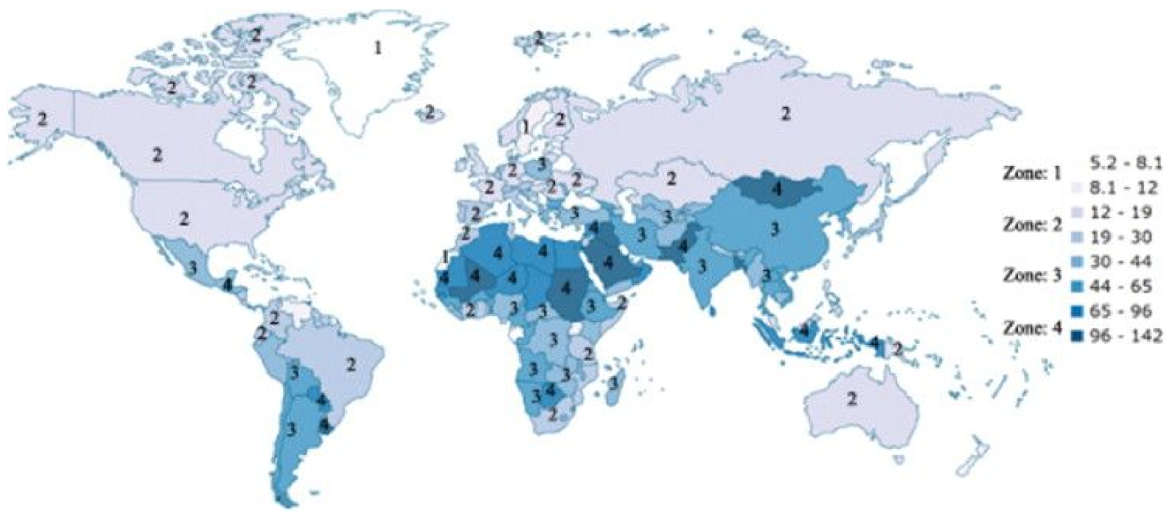


FIGURE 1: PM10 world map [μg/m3] [3]

The United States sits in zone 2, where dust generally does not heavily accumulate. When building a solar farm, it is critical to do the proper research and site planning to ensure maximum efficiency. In areas such as California, desirable land often comes at a premium which can drastically reduce profit margins even before taking soiling into account. If panels are constantly dirty and provide less energy than they should, that area may not be suitable to house panels. Cleaning panels is an expensive endeavor and should be done as infrequently as possible to keep costs down. Once the panels are in place, it becomes unfeasibly expensive to relocate. This paper aims to make a recommendation on the optimal times of year to clean the solar panels based on soiling and energy production data.

Chapter 2: Background

The objective of this project was to develop a model that can determine if cleaning a large scale PV installation is economically feasible. This model will take specific factors from the site being studied and give an estimate on the consecutive clear days required in the future to make cleaning the farm profitable. This information can then be compared with weather forecasts and rainfall patterns in the area to make a much more informed decision about when to clean.

One of the most critical pieces of this project was collecting accurate data, as it was needed to properly model our cleaning schedule with a program. We employed multiple methods of collection in order to get accurate data. One key method is outdoor exposure testing for long durations, as it proves to be the most effective means of evaluating soiling on solar panels. By evaluating the connection between solar panel soiling and time, we can create a more accurate schedule for cleaning the panels. With a proper cleaning schedule, a solar farm could increase its energy production rate. Based on existing cleaning schedules and dust collection data in general, we can expect our program to suggest that a cleaning every 1-2 months will optimize the total energy produced by the panels. However, just because this might result in more efficient energy production does not mean it is the most cost effective cleaning schedule for our solar farm. The standard estimate to clean a single panel is around $1. On a large solar farm, it can easily cost tens of thousands of dollars to fully clean the panels.

The Gold Tree Solar Farm was our case study for the duration of the project. California Polytechnic State University, San Luis Obispo partnered with local company REC Solar to install an 18.5 acre solar farm, capable of generating 11 million KWh per year [4]. It is estimated to save Cal Poly over $10 million in utility costs over the next twenty years [4] as well as provide the intangible environmental benefits of transitioning to alternative, clean energy sources. In large scale PV installations such as the Gold Tree Solar Farm, soiling (the accumulation of dirt and other debris) on the panels can account for up to a 6% reduction in efficiency [1]. With such a large amount of energy being produced at the installation this loss is very significant in terms of both profit margins and energy production. However, an industry standard estimate for cleaning panels up to $1 per panel. From these numbers a cleaning for an installation the size of Gold Tree will be somewhere from $8000 $16,000 and must be weighed against the potential benefits. The objective of this project is to create a robust model of the effects of soiling on solar panels and then use this model to create a recommendation program for optimal cleaning times. This model and program will take into account soiling losses, cost of cleaning, effects of cleaning, and how weather events alter soiling rates.

Chapter 3: Project Planning

This section of the report was written before the bulk of the project was completed, during EE 460. Many of these claims and assumptions didn't pan out exactly as expected but this provided a good framework to work through the project in. The global pandemic that occurred during this project also had a significant effect on the ultimate program created. Final conditions and decisions are discussed later in the report.

Customer Needs Assessment

In large scale PV arrays, soiling can contribute significantly to efficiency losses. With such a large amount of energy being produced small percentage drops can add up to a significant amount of profit loss. Our customer requires a schedule for cleaning the panels to optimize profits. This schedule should be derived from a sophisticated model of how soiling affects efficiency and a cost benefit analysis of cleaning frequency that should take into account factors such as weather. Each of these aspects will require a significant amount of analysis to correctly implement.. The model will need to take in soiling level, likelihood of a weather event within the cleaning window, previous soiling data, data on the increased profit of cleaning, and finally cost estimates of cleaning so the program can then make a recommendation to optimize profit. These ideas were synthesized into requirements and specifications as shown below in Table 1.

Requirements and Specifications

The program we create will act as our final product, to be used at solar farms to increase profit margins. We were able to simplify the marketing requirements into four goals that will ensure our product is attractive to the customer. These marketing requirements can be seen below at the bottom of Table 1. From the marketing requirements we were able to specify many engineering specifications. These specifications will guide us in the creation of our model and will guarantee our program functions properly and meets expectations. These engineering specifications can also be found in Table 1. Many of these specifications are data oriented as the project will heavily focus on the collection of data from the Gold Tree Solar Farm.

TABLE 1: Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
1	Determine cost of cleaning all panels on a per panel basis such that the results can be applied generally.	The cost of cleaning the panels is a major factor in the discussion of how often they can be cleaned.
1	Determine energy gained after cleaning.	The energy gained after cleaning a panel will allow us to see the effects of soiling.
1	Determine additional loss that would occur if not cleaned.	Determining the loss of energy when the panels are not cleaned will help in the calculations for energy gained from cleaning vs. not cleaning.
2	Determine a way to quantify soiling.	Any debris that impedes sunlight from getting to the panels and causing a loss of efficiency will be quantified with energy loss.
2	Determine type of relationship soiling has with time (linear, exponential, ect.)	Learning the soiling relationship with time will allow us to judge the best time to clean the panels.
2	Determine type of relationship soiling has with efficiency and thus profits	Calculate energy loss due to soiling and compare that against the price per kWh that would've been sold.
3	Examine how well a rainstorm cleans the panel in comparison to manually washing. Examine data before and after.	Rain may clean the panels for us during the rainy seasons. A rainstorm will likely cut the soiling rate, but will not return the panel to a completely clean state like a wash would.
3	How weather events affect the cost ratio of cleaning vs. soiling.	Cleaning the panels before a rain storm could end up costing a large sum of money. However, there could be a point of cleaning at a certain time

		ahead of expected storms to keep a low level of soiling through the rainy season if possible, depending on how well rain cleans the panels.(previous spec)
4	Use multiple sets of data from different sources to ensure accuracy of our conclusions (curve tracer, direct energy measurement, ect).	The more sources of data we collect from, the more accurate our data will be, allowing our final calculations and decisions for the cleaning schedule to better.
5	Ensure that conclusions are applicable over different PV array types such as split cell or tracking and non-tracking panels.	We want to ensure that the data and recommendations provided will not be limited to a single type of panel. Keep it applicable to different panel manufacturers.
5	Study cost and effectiveness of different cleaning methods.	A quicker cleaning method will likely cost less to implement but will also likely not clean the panel as thoroughly.

Marketing Requirements

1. Ensure gain in energy due to cleaning panels is much larger than the cost of cleaning the panels. Optimize this balance.
2. Base recommendation off of robust model for soiling of panels.
3. Include weather events such as a rainstorm in scheduling.
4. Base data off of multiple collection methods.
5. Includes analysis of value of cleaning on different PV arrays and of different cleaning methods

TABLE 2: Deliverables

Delivery Date	Deliverable Description
10/29/19	Cost Estimates and Gantt Charts
11/04/19	ABET Sr. Project Analysis
March 2020	Design Review
May 2020	EE 462 demo
May 2020	EE 462 Report

Functional Decomposition (Level 0 and Level 1)

The program will use variables such as soiling level, energy production, and weather as the prime considerations for a recommendation. These inputs will be used to create a model for energy loss due to soiling. Data taken in multiple formats will ensure that this program is accurate and can predict the changes in production that cleaning will have on the panels. The outputs in the level 0 block diagram are energy production data to be used as feedback and a cleaning recommendation.

TABLE 3: Block Diagram Input, Output, and Functionality table

Module	Soiling on PV Panels Guide Timing of Cost Effective Cleaning
Inputs	-Soiling Data (involves efficiency) -Energy Production Data (feedback) -Weather Data (Sunlight, Rain, Wind, ect.)
Outputs	-Energy Production Data (results from cleaning) -Cleaning Recommendation or Schedule -Estimated economic benefit from cleaning at recommended time
Functionality	To collect data from PV panels and come up with a way to quantify soiling and its relationship to energy production.

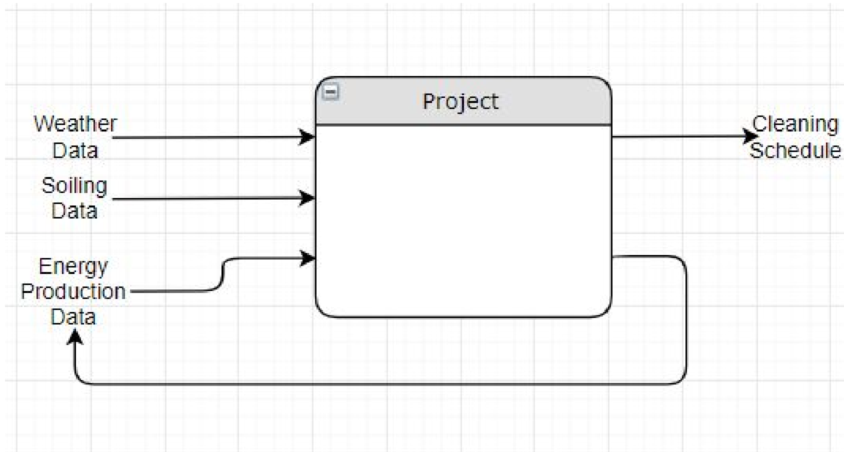


FIGURE 2: Block Diagram Level 0

The level 0 block diagram is shown above in Figure 2. It is quite basic, illustrating the inputs and outputs to the program. The inputs can be seen as weather data and soiling data, and the feedback loop, which is energy production data. The outputs of the system are the energy production data, which is looped back into the system as an input, and the cleaning schedule, which is the final output of our program. When the model is functional and accurate, we will deliver a program that can generate a cleaning schedule for solar farms based on that model.

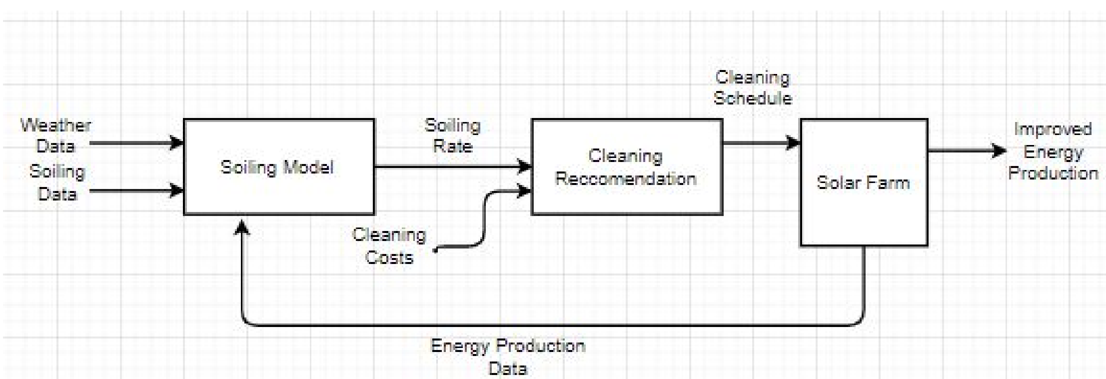


FIGURE 3: Block Diagram Level 1

The level 1 block diagram, shown in Figure 3 above, has more detail and is more informative than the level 0. It shows how the data will populate our model and how the model will be used to create a cleaning recommendation. It also includes more inputs such as cleaning costs, which along with the soiling rates, allow us to make our cleaning recommendation. The cleaning recommendation is then tested at the Gold Tree Solar Farm, allowing us to improve upon our model and more accurately predict optimal cleaning times.

Gantt Chart

The projected pace of our project is shown below in the Gantt Chart in Figure 4. Most of the preparation and project planning is to be completed in the fall quarter. We begin to collect data at the start of winter quarter and past data should be available for collection. At the start of winter quarter we will begin to start cleaning the panels and developing an experimental cleaning schedule as well. By week 6 of winter quarter, we will start the analysis of our collected data in order to start making our cleaning schedule by week 8. After data collection the plan is to begin analyzing our data and writing the report encapsulating our findings. The report will recommend a cleaning schedule to maximize efficiency of the solar panels.

#	Fall Quarter	Prerequisites	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11
1	Abstract (Proposal) V1												
2	Requirements and Specifications				Due								
3	Block Diagram					Due							
4	Literature search						Due						
5	Gantt Chart and Cost Estimate	1, 2, 3, 4						Due					
6	ABET Sr. Project Analysis	1, 2, 3, 4, 5							Due				
7	Requirements and Specifications V2 + Intro	1, 2, 3, 4, 5, 6								Due			
8	Report V1	1, 2, 3, 4, 5, 6, 9								Due			
9	Advisor Feedback Due						Due					Due	
10	Report V2	7, 9											Due
11	Requirements and Specifications Presentation	2				Due							
12	Report V1 Presentation	1, 2, 3, 4											Due
13	Resume and Cover letter		Due										
14	Sensitivity Analysis	3, 4						Due					
15	Reverse Engineering										Due		
16	Final Exam												Due
17	Start data modeling using previous data												
18	Collecting Data	17											
19	Continue Research into cleaning schedules	4											

#	Winter Quarter	Prerequisites	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11
17	Start data modeling using previous data												
18	Collecting Data	17											
19	Continue Research into cleaning schedules	4											
20	Clean Panels	17, 18											
21	Analysis of data collected	18, 20, 23											
22	Construction of cleaning schedule	21											
23	Develop experimental cleaning schedule	17, 19											
24	Use experimental schedule, panel cleaned intermittently, and uncleaned control panel	23											
25	Interim Report Milestone	21, 23											Due

#	Spring Quarter	Prerequisites	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11
18	Collecting Data	17											
21	Analysis of data collected	18, 20, 23											
22	Construction of cleaning schedule	21											
26	Compile research data and analysis into report	21, 22											
27	Turn in final report	26											

FIGURE 4: Gantt Chart

Cost Estimate

The cost estimate table below shows the cost breakdown of the project. There are very minimal costs associated with generating the program. The most expensive portion would be our labor associated with this project, the formula behind determining labor costs are tabulated below. Everything else except transportation costs and panel cleaning supplies will already be available to us. We don't anticipate more costs accruing during the term of this project.

TABLE 4: Cost Estimate

Item	Cost	Explanation
Labor	$\$4842 = \frac{35(100 + 4(120) + 250)}{6}$ For a 3 person group: $14,525	Since this project is research and data/analysis based, most of the cost will fall into the labor category. The hourly rate of $35, with an Optimistic minimum expected time of 100 hours, an expected time of 120 hours , and a pessimistic expected time of 250 hours per person. This is a 3 person group.
Transportation Costs	$12.80	It is 4 miles to the solar farm and back to Cal Poly and we're anticipating around 20 trips.. Assuming $4 a gallon and the average mpg of a car in the United States to be ~25mpg, comes out to around $0.64 per trip.
Water and squeegees to clean the panels	Water price per 2 rows of panels: $\$8.13 = (.04)(20)\frac{(6 + 4(10) + 15)}{6}$ Total = $20.13	Using a value of about 4 cents per gallon of water, the following was calculated. We expect to clean the panels at least 6 times, most likely 10 times, and at most 15 times. Using an estimated 20 gallons of water to clean 2 rows of panels, this costs us about $ to wash the panels. Squeegees can be acquired for about $4 each, giving $12 for 3.

Chapter 4: Overview of Data Collection

There were two sets of data from the Gold Tree Solar Farm used to calculate distinct soiling rates. Method 1 uses an ARES Soiling Measurement Station to perform irradiance and short circuit current measurements to calculate a soiling rate [2]. Method 2 uses direct measurement of energy production using inverter data from the farm using a real-time monitoring program, GPM Portal from GreenPowerMonitor [5]. The GPM portal provided the daily precipitation amount at the solar farm as well. This data used in this report was collected from January 2019-March 2020.

The ARES Soiling Measurement Station uses two small panels to gather irradiance intensity, temperature, and voltage. One of the panels self cleans daily, to be the control for baseline irradiance. The other panel was allowed to soil over the course of the experiment and a ratio was taken between the clean and dirty panels' production data. The computation for soiling rates was done internally by the ARES.

Method 2 uses data taken directly from the inverters, which was more complex. To measure the daily energy production accurately, data from two different sets of panels were collected. At the Gold Tree Solar Farm, rows of panels are attached to single inverters. There are many sets of inverters and their associated rows. The two inverters used in this project are labeled Inverters 29 and 31. When either inverter is referred to in this paper, it references the row of panels connected to the aforementioned inverter.

To gauge an appropriate soiling rate from energy production, one row of panels was regularly cleaned while another was allowed to soil throughout the year. Inverter 29 was cleaned periodically while Inverter 31 was allowed to soil. Ideally, Inverter 29 would've been cleaned every single day to allow collection of valid data. However, a row of panels took a few hours to clean with the limited manpower available and was not feasible to do every day. Originally, a soiling rate was computed by plotting the percent difference in daily energy production between Inverter 29 and Inverter 31. The slope of the daily percent difference represented the rate at which the panels soiled. Unfortunately this rate was inaccurate because many of the days that our data included was invalid. The actual days when Inverter 29 was cleaned provided the only valid data to compare the effect soiling has on Inverter 31, other days both panels had some degree of soiling present meaning the control was invalid. The rest of the data helped with visualization of trends but was not used to compute a final soiling rate. This rate was computed through a linear trendline placed on the valid inverter data. The result was a more constant slope as the percent difference in energy production would not increase as much over time.

Another factor that had to be considered when making this model was the weather. Over the course of the year, weather had a significant impact on the soiling of the panels. To examine the effect rainfall had on the panels, every weather event was recorded and the difference in energy production between inverters the next day was examined. Unfortunately the weather events that occurred over the course of data collection did not provide enough valid data to paint a realistic picture of how the rainfall cleans the panels. For the purposes of our program it was assumed that rainfall completely cleans panels in the same way that a cleaning would. This assumption is defensible because an amount of dirt remaining on the panels after rainfall can only result in an underestimation of profits, never an overestimation. The worst case scenario is that a cleaning recommended by the program is actually more financially sound than predicted.

Chapter 5: Data Analysis

The bulk of the time spent on this project was data analysis. The objective was to glean an understanding of the rate at which soiling caused the production of panels to fall. This rate can then be used to inform the model and determine the optimal cleaning days at the farm. Through the extensive data analysis many different soiling rates were determined, and will be discussed below.

The first pass at the data consisted of us summing the energy produced by each inverter over each day then dividing the larger (clean) energy by the smaller (dirty) energy. This resulted in a percentage that represented the amount of energy that the dirty panel was missing. The following graphic represents this data after heavy processing.

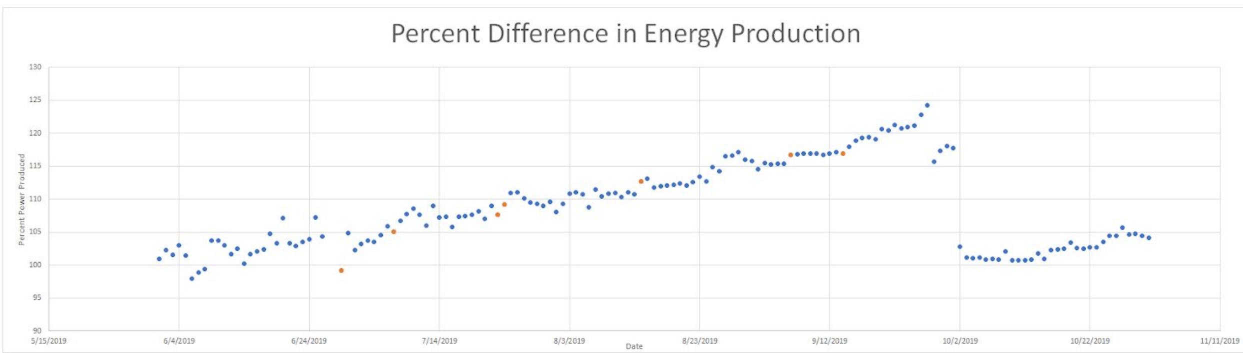


Figure 5: Percent Difference in Energy Production

As seen above the amount of power difference grows as the panels remain uncleaned. The difference continued to grow until it finally rained in late September, essentially bringing the panels back to the same production rate. The soiling effect then continues and the difference begins to rise again. The orange points on the graph are days the panels were actually cleaned, thus the valid data to determine a soiling rate from. Other points are being compared to a not fully cleaned panel, and are therefore invlaid due to the lack of a consistent control variable.

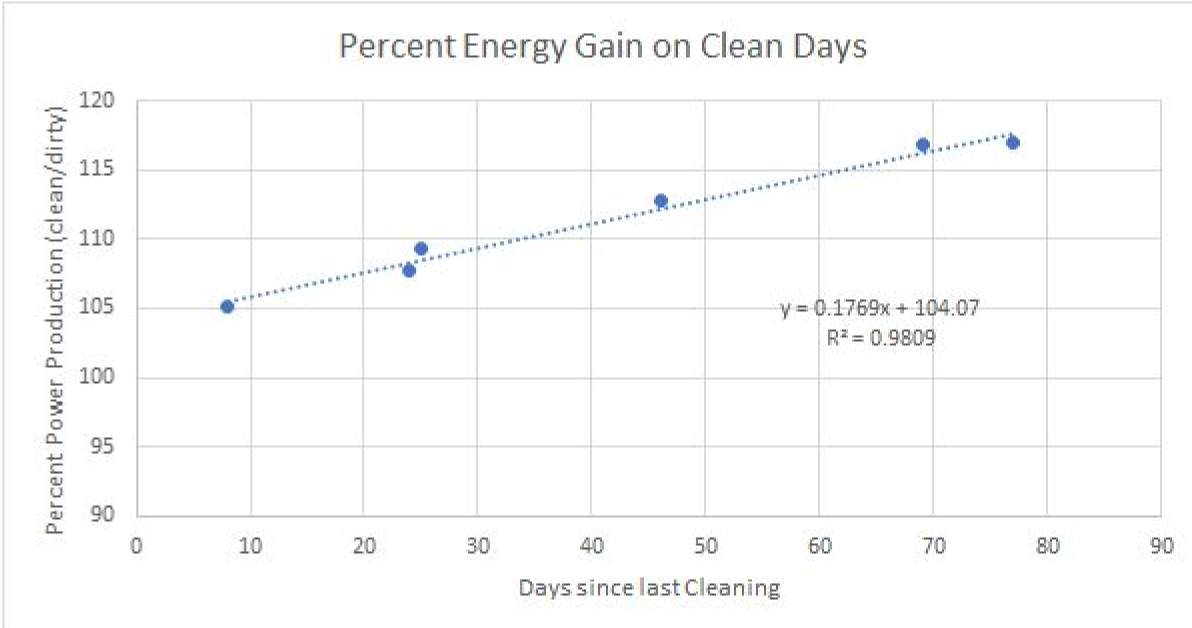


Figure 6: Percent Energy Gain on Cleaned Days

The graph above shows the valid data from the overall trend. Different regression models such as exponential and power functions were examined but linear was by far the best fit for the situation. The trendline's slope in this graph represents the soiling rate. This means that each day a panel goes unclean it will produce 0.1769% less energy. This rate allowed the model to begin to be built. After this rate was established other data was processed to ensure that the rate was accurate. The inverter's daily active power was sampled next then compared in the same way the previous data was (% clean over dirty).

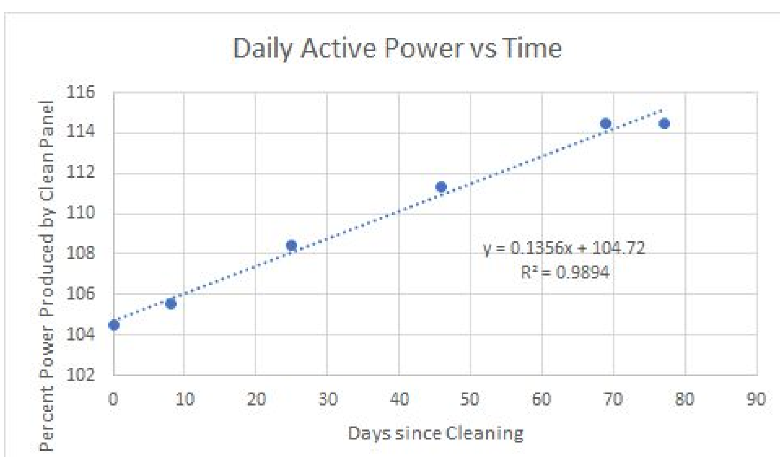


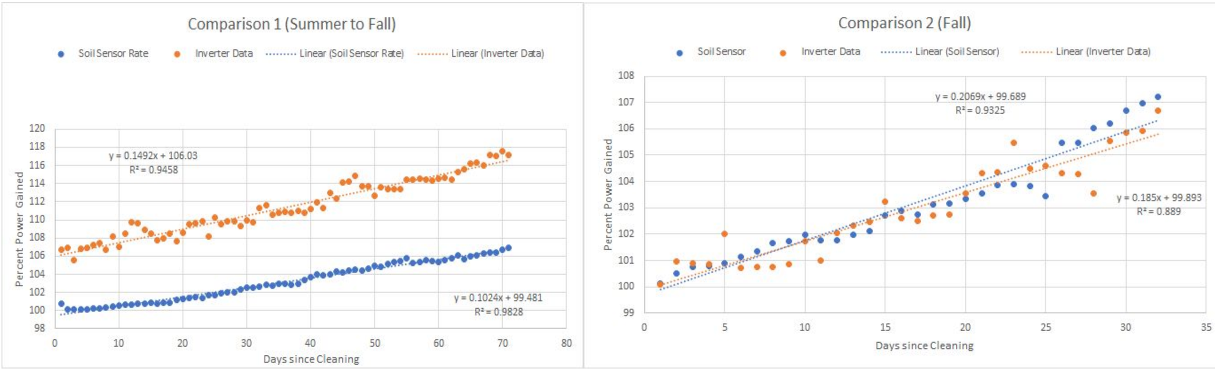
Figure 7: Daily Active Power vs Time

The figure above was derived in the same way as the last one, using days that the panels were actually clean as valid data points. It quickly became apparent that the data used to find the rate will have a significant effect. This is evidenced by the lower slope seen in the graph above.

More soiling rates were derived from data taken by the ARES. This data is advantageous because the ARES is able to clean itself every day. This is significant because it means that every datapoint is valid for analysis. This also resulted in a much smoother data set as the loss due soiling rate should be seen changing each day.

Figure 8: Comparison Between Data Collection Methods

As seen in the chart above the ARES's data had some significant variance from the inverter data from before. The offset in the first part of the graph is insignificant; it only appears because the ARES experiment started at a different time then the inverter data collection. The real difference is in the slopes and thus soiling rates.



Figures 9 & 10: Soiling Rate Comparisons 1 & 2 (Late Summer and Fall)

The two upward trends seen in the overall comparison are displayed with regression lines here. Interestingly the ARES rate swings in magnitude much more than the rate derived from the inverters. While the inverter data only swings about 0.02% between the different times the ARES rate changes a whole 0.1%, a significant number when dealing with energy on the order of magnitude that the farm produces.

With all of this variation between soiling rates it became clear that the soiling rate could not be expressed as a single number, but rather as a range of possible values. Throughout all of the data the lowest soiling rate observed was ~ 0.1024 % per day while the highest was ~0.2069 % per day. These values represent the extremes, most soiling rates fell between 0.15 - 0.18 %. Our best estimate for a yearly soiling rate at the Gold Tree Solar Farm is approximately 0.17%. This rate was used for the majority of further calculations. However, the program includes soiling rate as an input, allowing any situation to be examined.

Chapter 6: Cost-Benefit Analysis

To perform a monetary analysis using the soiling rates derived through the data required a number of smaller pieces of data to be collected in order to make calculations. First, an estimate of the daily energy produced needed to be estimated so that percentage loss could be converted into units of energy. For each month a daily potential energy was estimated using data from the farm's panels. Typical cleaning costs in the industry are about $1.00 per module. The operators of the Goldtree solar farm would likely pay approximately $16,000 for a cleaning. This value is used throughout our project as an example. For the initial cost benefit analysis a rate of $0.06 / kWh is used but since rates vary so much the program allows for any rate to be entered and examined.

Table 5: Daily kWh production for each month

Month	**Days in Month**	**Daily kWh production**
January	31	14,391
February	28	19,293
March	31	25,482
April	30	31,729
May	31	31,707
June	30	35,685
July	31	37,912
August	31	34,595
September	30	29,129
October	31	27,449
November	30	18,055
December	31	12,590

Once these preliminary pieces of data were collected it was possibly to begin constructing a model for the monetary loss due to soiling. An Excel sheet was used for preliminary modeling. To estimate the energy loss due to soiling, a cumulative loss percentage was calculated by tallying the days since the farm was last cleaned or rained on and then multiplying that count by the chosen soiling rate. This percentage was then multiplied by the day's corresponding estimated kWh production. This loss can then be multiplied by the kWh to cash conversion ($0.06/kWh) to give a dollar estimate of the loss on any given day. This loss can be tallied to give the cumulative cash loss.

Day	Days Since Cleaning	Weather?	Percent Loss	KWh Loss	Cumulative KWh Loss	Cumulative Cash
1/1/2020	0	0	0	0	0.00	$0.00
1/2/2020	1	0	0.0017	24.4647	24.46	$1.47
1/3/2020	2	0	0.0034	48.9294	73.39	$4.40
1/4/2020	3	0	0.0051	73.3941	146.79	$8.81
1/5/2020	0	1	0	0	146.79	$8.81
1/6/2020	0	1	0	0	146.79	$8.81
1/7/2020	0	1	0	0	146.79	$8.81
1/8/2020	1	0	0.0017	24.4647	171.25	$10.28
1/9/2020	0	1	0	0	171.25	$10.28
1/10/2020	1	0	0.0017	24.4647	195.72	$11.74
1/11/2020	0	1	0	0	195.72	$11.74
1/12/2020	0	1	0	0	195.72	$11.74
1/13/2020	1	0	0.0017	24.4647	220.18	$13.21
1/14/2020	0	1	0	0	220.18	$13.21
1/15/2020	0	1	0	0	220.18	$13.21
1/16/2020	0	1	0	0	220.18	$13.21
1/17/2020	0	1	0	0	220.18	$13.21
1/18/2020	1	0	0.0017	24.4647	244.65	$14.68
1/19/2020	2	0	0.0034	48.9294	293.58	$17.61
1/20/2020	0	1	0	0	293.58	$17.61
1/21/2020	0	1	0	0	293.58	$17.61
1/22/2020	1	0	0.0017	24.4647	318.04	$19.08
1/23/2020	2	0	0.0034	48.9294	366.97	$22.02
1/24/2020	3	0	0.0051	73.3941	440.36	$26.42
1/25/2020	4	0	0.0068	97.8588	538.22	$32.29
1/26/2020	5	0	0.0085	122.3235	660.55	$39.63

Figure 11: Sample of Base Loss Excel Model Estimates

This method only provided an estimate of the losses due to soiling in a no-cleaning situation. Determining the profits from a cleaning required much more analysis. A second identical set of data was created, calculating the same numbers as the first. The only difference between the two sets is that one's "days since cleaning" tally is only reset by weather events while the other is reset by both weather events and cleanings. The weather and cleaning loss can be subtracted from the weather only loss to see the loss avoided by the cleanings. This gives an estimate of the profit as a result of the cleaning. Finally, $16,000 was subtracted per cleaning from this difference to represent the final profit or loss. The soiling rate and cost per kWh can be adjusted to examine different possibilities. This can be seen in the figure below. The yellow cells represent inputs to the model, and the future program.

Day	Weather?	Days Since Cleaning	Cleaned?	Percent Loss	KWh Loss	Cumulative KWh Los	Cumulative Cash Loss	Savings From Cleaning				KWh/month		KWh/Day
1/1/2020	0	0	0	0	0	0	$0.00	$0	0	1	Jan	446132	31	14391.35484
1/2/2020	0	1	0	0.0017	24	24	$1.47	$0	0	2	Feb	540226	28	19293.78571
1/3/2020	0	2	0	0.0034	49	73	$4.40	$0	0	3	Mar	789941	31	25481.96774
1/4/2020	0	3	0	0.0051	73	147	$8.81	$0	0	4	April	953777	30	31792.56667
1/5/2020	1	0	0	0	0	147	$8.81	$0	0	5	May	982934	31	31707.54839
1/6/2020	1	0	0	0	0	147	$8.81	$0	0	6	June	1070552	30	35685.06667
1/7/2020	1	0	0	0	0	147	$8.81	$0	0	7	July	1175275	31	37912.09677
1/8/2020	0	1	0	0.0017	24	171	$10.28	$0	0	8	August	1072469	31	34595.77419
1/9/2020	1	0	0	0	0	171	$10.28	$0	0	9	September	873889	30	29129.63333
1/10/2020	0	1	0	0.0017	24	196	$11.74	$0	0	10	October	850941	31	27449.70968
1/11/2020	1	0	0	0	0	196	$11.74	$0	0	11	November	541662	30	18055.4
1/12/2020	1	0	0	0	0	196	$11.74	$0	0	12	December	390292	31	12590.06452
1/13/2020	0	1	0	0.0017	24	220	$13.21	$0	0					
1/14/2020	1	0	0	0	0	220	$13.21	$0	0	Cleaning Cost	16000			
1/15/2020	1	0	0	0	0	220	$13.21	$0	0	RATE	0.17			
1/16/2020	1	0	0	0	0	220	$13.21	$0	0	Cost Per KWh	0.06			
1/17/2020	1	0	0	0	0	220	$13.21	$0	0					
1/18/2020	0	1	0	0.0017	24	245	$14.68	$0	0	Profit	-$8,039.28			
1/19/2020	0	2	0	0.0034	49	294	$17.61	$0	0					
1/20/2020	1	0	0	0	0	294	$17.61	$0	0					
1/21/2020	1	0	0	0	0	294	$17.61	$0	0	Greater Than	1			
1/22/2020	0	1	0	0.0017	24	318	$19.08	$0	0	Reset To	0			
1/23/2020	0	2	0	0.0034	49	367	$22.02	$0	0					
1/24/2020	0	3	0	0.0051	73	440	$26.42	$0	0					
1/25/2020	0	4	0	0.0068	98	538	$32.29	$0	0	Clean Day	8/11/2020			
1/26/2020	0	5	0	0.0085	122	661	$39.63	$0	0					

Figure 12: Sample of Additional Excel Modeling to Determine Profit/Loss

We collected the precipitation data for San Luis Obispo over the previous year from the GPM Portal. The rainfall event was logged in the model and possible cleaning days were tested. Unfortunately no days selected resulted in any profit at $0.06 per kWh and a medium soiling rate of 0.17% / day. The best possible situation resulted in a $8,039 loss. At a more aggressive soiling rate of .2% / day a $6,634 loss still occurred. The frequency of precipitation throughout the year made it impossible for the panels to accumulate enough soiling to justify the cost of cleaning. In other areas with different climates and inherent soiling rates and well as different financial situations there is a possibility for profit. To examine these situations all that is needed is an estimate on energy produced throughout the year, a soiling rate, a cost of cleaning estimate and the rate at which kWh are sold from the farm.

Upon reaching this conclusion, we began to research other possible ways that our model could be beneficial financially to solar farm operators. There are many cases where one entity maintains and sells energy to another entity, who then sells energy to the grid. There are arrangements where two entities may split the proceeds from energy generated but may not split the maintenance equally. If the solar farm improves efficiency, both organizations benefit as more energy is sold. A single entity shouldering the entire cost will always lead to a financially unbalanced situation that will result in less frequent cleaning and thus lower production. If these companies were to split the costs of a cleaning with the solar farm equitably, it is possible that both groups could make money. Not only is this possibly financially beneficial, more electricity is generated by renewable sources. The improvement in efficiency of the solar farm means less electricity is generated by burning fossil fuels. We chose to add a functionality to our program that can split the costs and profits between two organizations, allowing split situations to be analyzed.

Chapter 7: Predictive Program

The final step in the project was to create a predictive program that would provide information to the user about how long it will take to break even cleaning solar panels. This program takes in 7-9 different inputs from the user at the time of running the program: the soiling rate of the region/season, the amount of companies involved in the process(1-2), the price that the first company sells energy in kWh, the price that the second company sells energy in kWh, the cost of cleaning the solar panels, the number of days since the last cleaning, the current month, the current day of the month, and a user defined split of payment between the two companies (given that 2 is entered for the number of companies input). Furthermore, the average daily energy values for each month are read in from an excel sheet containing the info. Currently, the values in the sheet represent the Gold Tree Solar Farm's energy production rates, but the excel sheet can be altered to allow for this prediction algorithm to be used for different farms. With all of these given inputs fulfilled, the program will start the process of analyzing energy savings and predicting the amount of days without rain that would be needed for the given company/companies to break even.

The general flow process of the program can be seen in Figure 13 below. The outputs for the program differ based on whether 1 or 2 was input by the user for the number of companies involved in the process. If a value of 1 was input, then the program outputs a graph showing the savings of the company compared to the cleaning cost of the panels. When the two lines meet, this is the day that the company starts making a profit off of the cleaning. Furthermore, a table is output into the command window displaying the break even day and the amount of profit that the company will have by the end of that day. An example of the single company outputs can be seen below in Figure 14. Finally, if a value of 2 was input for the number of companies involved in the process, five different graphs are output in order to show five different possible scenarios of payment between the two companies. The different scenarios that are taken into account in this program are: company 1 pays for the entire cleaning, company 2 pays for the entire cleaning, the two companies split the cost at 50%, the two companies split the cost at the user input percentage, and the two companies put all savings back into the payment. Just like the single company scenario, there is also a table output to the command window. This table displays the names of the different scenarios, the break even day, and the savings for each company by the break even day. The two company output of the program can be seen below in Figure 15.

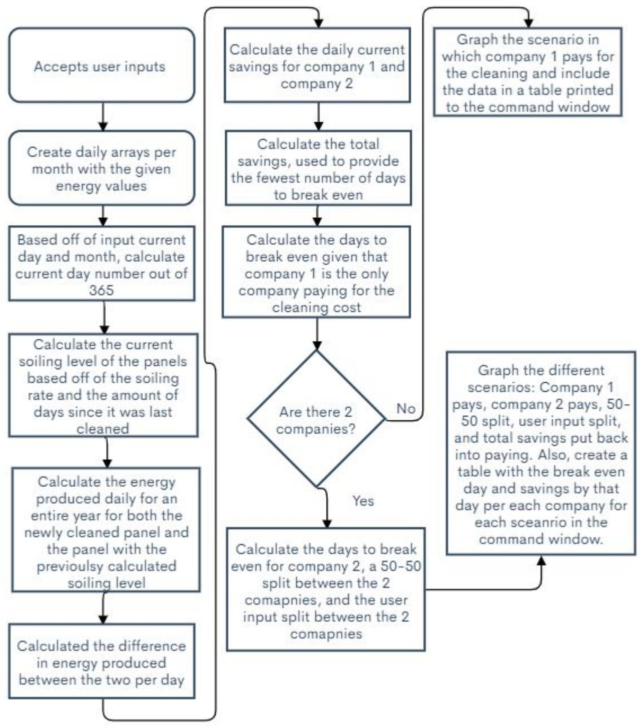
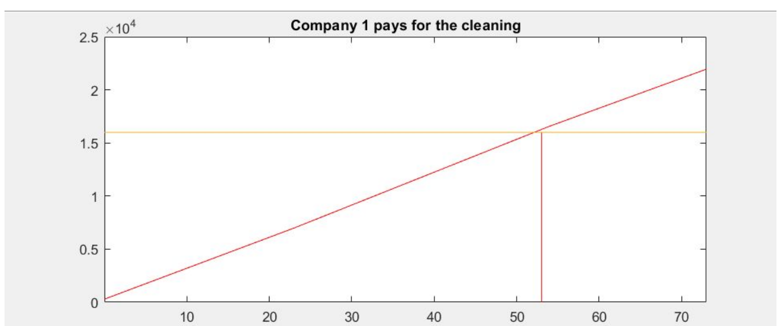


Figure 13: Flowchart for the predictive program



Payment_Method	Amount_of_days_till_even	Amount_of_savings_for_company1_by_day_even
Total	53	269.4
C 1	53	269.4

Figure 14: Program output for a single company

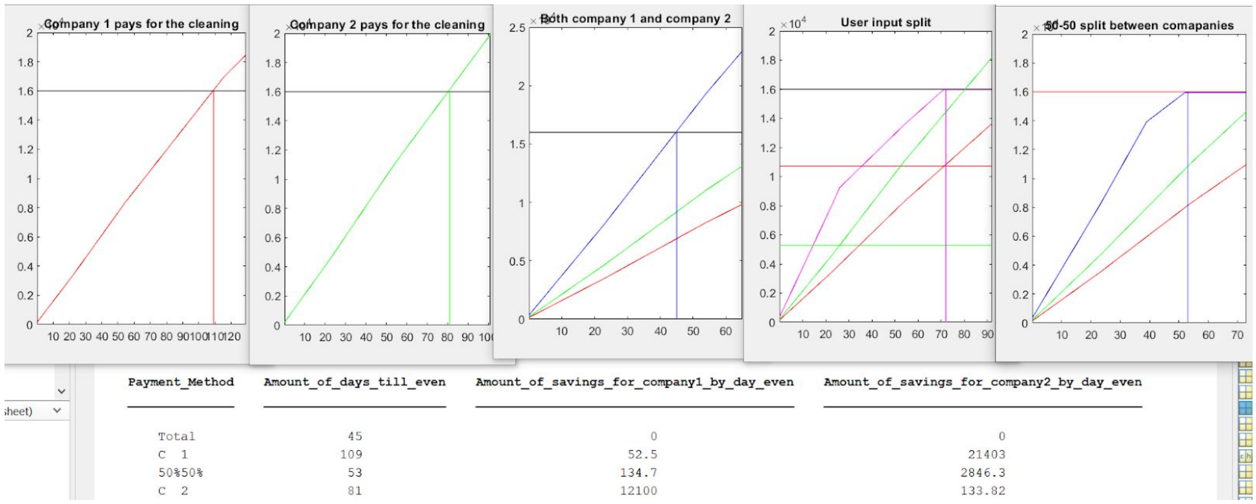


Figure 15: Program output for two companies

As can be seen in Figure 15 above, for the graphs that use both companies, there are multiple different lines on the graph. In each case, the red line represents the savings of company 1 and the green line represents the savings of company 2, just like in their own payment graphs. Furthermore, for the user input section, there are also horizontal lines drawn for each company's own payment requirement. Once again, the red line represents the amount that company 1 needs to pay and the green line represents the amount that company 2 needs to pay. This helps the user to see the amount of savings that a company can make by the break even day.

Chapter 8: Conclusion

General Recommendation

For more general cases, selling energy at market rates may make it more profitable to clean solar panels on a more regular basis. Location plays the largest role in the economic feasibility of cleaning panels, as it affects soiling rate, value of energy and frequency of rainfall. In areas with large amounts of sand or dust, coupled with low annual rainfall, it makes perfect sense to clean regularly. By not doing so the solar panels are losing a large amount of energy relative to what they could be making and selling. Each case should be judged on an individual basis with some weather generalizations based on location. Our model can give useful estimates to inform these decisions, requiring a small amount of data to be collected to model a particular situation.

Case Study - Gold Tree Solar Farm

As the soiling rates were computed for our case study, it became clear that the potential gain in energy from cleaning the panels was not worth the cost to clean them. At a fixed price of $0.06 per kWh and reliable rainfall throughout the wet season, a single entity couldn't realistically make a profit with even one cleaning in our model. The low price at which they sell energy is responsible for this imbalance. At this point we decided to look into potential alternatives or solutions that would assist entities in turning a profit and provide more clean energy to the grid. An alternative situation where entity 1 sells energy at a rate of $0.06 / kWh to entity 2 and then entity 2 sells to the grid at $0.13 / kWh was examined. The resale price is higher than entity 1's sale price, meaning an increase in energy will improve entity 2's profit more than that of entity 1. A higher price per kWh means more profit is lost due to the effects of soiling. If entity 2 were to invest in part of these cleanings and their potential profits are taken into account, the amount of time it takes to break even from the cleaning payment is drastically reduced. Even if entity 2 partially funded a cleaning, a greater profit margin for both organizations would occur and the installation would also provide more clean energy to the grid.

Future Improvements

User Interface

The program is written in MATLAB so all the variables defined by the user are implemented using the command window. A visual and intuitive UI would make the program more accessible to people. MATLAB is an expensive software and many will not want to purchase additional software to run our program. A web application would be the next step in development.

More Gold Tree Data

A longer period of study would have been ideal to collect more data and improve our model. While coastal California remains mostly temperate throughout the year, examining rainfall patterns and energy data over the course of several years would be valuable. The soiling rate would be able to be forecasted with more accuracy during certain months and show a more accurate picture of soiling over the course of a year.

Multiple Case Studies

The Gold Tree Solar Farm data was available to us thanks to a partnership with Cal Poly. Our model is reliant on data collected from that specific farm so there may be unforeseen location factors that affect the efficiency of the panels. The program allows the user to input a custom soiling rate to adjust for differences in location, however having pregenerated rates would be a good option for users that do not have the time or resources to conduct a soiling study.

Weather Model

One of the biggest assumptions we were forced to make was about rainfall. With valid data from only a few rainfall events we were not able to properly identify the amount a certain amount of rain would clean the panels. A long term study would have to be run to parse out this type of data but it would allow a much more accurate model to be produced. The current version assumes that all significant rainfall events fully clean the panels, returning them to full production. This assumption is made to purposefully underestimate profits as an overestimation of profits is much worse than a small unexpected profit after cleaning. If a ratio of rainfall depth to change in soiling were established this assumption would no longer be necessary, allowing the profits from the partial soiling left after rainfall to be analyzed.

Appendix A: Senior Project Analysis

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

Student's Name: Student's Signature:

Jack Puckett

Max Sosa

Brandon Grossman

Advisor's Name: Dale Dolan Advisor's Initials: Date:

- **1. Summary of Functional Requirements**

  In large scale PV arrays, soiling can contribute up to 6% of total efficiency losses. With such a large amount of energy being produced small percentage drops can add up to a significant amount of profit loss. Modules may be cleaned to reduce losses, but this comes with an offsetting economic cost. A quantification of energy losses, and their corresponding economic loss, allows us to determine an optimal cleaning schedule depending on the level of soiling and corresponding power loss. Our customer requires a program to help schedule cleaning the panels to optimize profits. This schedule is derived from a sophisticated model of how soiling affects efficiency, a cost benefit analysis of cleaning frequency and considers other factors such as rain and weather.

- **2. Primary Constraints**

  The most limiting aspect of the project was the collection of accurate data. When studying PV systems, it is difficult to control the variables of the experiment due to the weather and the long term nature of energy production. Each hour of each day presents a unique profile of temperature, irradiance, and other factors that can affect production. It was difficult to isolate the effects of cleaning the panel from all of these other variations; careful and accurate data collection and normalization procedures helped to ensure the efficiency variations we record are actually due to cleaning. This project used Gold Tree Solar Farm as a case study, with estimates and recommendations based on the site specific data we collected. However, the model we created can be applied to any PV array provided sufficient data can be collected to be used as inputs.

Another limiting factor is the weather. To accurately include rainstorms in our cleaning recommendation we needed to observe and collect data on the effects of rain of the panel's cleanliness. The unpredictability and relative infrequency of weather events made it very difficult to collect data on these events. This made modeling the effects of the weather events nearly impossible and forced assumptions to be made.

At the beginning of the project, we hypothesized that it may never be economically beneficial for the Gold Tree Solar Farm to clean panels. After we verified our hypothesis with the data collected, we decided to look at alternative ways to improve profits. If two entities were to split the costs for a cleaning, it would become economically feasible to clean panels more often. This gave us the idea of adding a function to the program to split costs and profits between two organizations and analyze profits in such a situation.

- **3. Economic**

This project depends on our 3 members collecting data and analyzing that data to create a predictive program for cleaning solar panels. Based on our research, the financial break even date for a certain cleaning situation is estimated. This program we create will affect the frequency that contractors are hired to clean the panels. The aim is to maximize the electrical energy as well as profit collected from the sun at this specific Solar Farm. With larger portions of the energy grid relying on alternatives such as solar, the use of fossil fuels should decrease. This comes at the cost of water and labor to clean the panels, but our program aims to minimize costs while maximizing the energy gains.

The only costs that will accrue for the duration of this project will be transportation, cleaning supplies, and our labor. The ARES Soiling Measurement Station was already installed at the farm and will not be included in our costs. We estimated transportation at approximately $13, cleaning supplies at $20, and our labor at $14,525 ($35 an hour, 3 people). However, this is a low budget project and the final product is intended to maximize profit and energy production. We were not paid and Professor Dolan provided transportation and cleaning supplies. The software used to create our model and program, Microsoft Excel and MATLAB respectively, was provided free of charge by Cal Poly. Data collection was done through GreenPowerMonitor, the monitoring system that supplied inverter data from the Gold Tree Solar Farm.

Estimates show that losses from 1.2% up to 6% can occur from soiling on a large scale PV installation[1]. The Gold Tree Solar Farm generates an estimated 11 million kWh per year. An increase in production could lead to tens of thousands of dollars more per year for solar farm operators. The complex part is making sure this profit outweighs the cost of cleaning.

Based on the layout of the Gantt chart, we expected to have the schedule fully developed in about 20 weeks. Through these twenty weeks, we expected to spend anywhere from 4-8 hours a week on the project, giving us an average of 120 hours altogether on the project per person. In actuality, work was spread out from the summer of 2019 until spring of

2020. The early work involved regularly cleaning the panels to generate valid data and learning about PV systems. Later this data was analyzed and conclusions were used to inform an excel model. Finally all of this was synthesized into a MATLAB program capable of evaluating the likely break even date for a specific situation.

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

The most limiting factor to using the program would be the collection of data on soiling at the site the schedule is being created for. Each solar farm will have a unique soiling profile due to variations in surroundings, weather, and climate. Once the data is collected and the soiling rate determined, the program will be able to instantaneously make estimates. Data collection can take a few months up to many years, plans must be made accordingly.

Developing this product is mostly a question of labor. From our cost estimate the creation of a model will cost ~$20k. This assumes three workers working approximately 140 hours of work each. In order to ensure profit from the creation of this program, the product would have to make $20k in total sales. This recommendation is intended to make the user money, not cost them. An extremely optimistic estimate for this profit would be 5% of the farm's existing production. After the initial creation of the program, applying it to another site is much less complex, only requiring a determination of soiling rate, average production numbers and knowledge of the financial situation of the array.

- **5. Environmental**

There are very few negative environmental impacts associated with the project. Heavy metals and resources from the earth were involved with creating the electronics within the panel, however this project aims to improve the management of existing alternative energy sources. Cleaning panels will require the use of clean water, but aside from this there are really no direct negative environmental impacts. Solar farms will be able to use capital and resources more efficiently, so less of our energy will come from non-renewable sources. If humans are able to shift our energy production needs to renewable resources it will benefit the environment, and this program aims to make that transition more profitable.

- **6. Manufacturability**

This project consists entirely of data analysis and code, meaning manufacturing is not applicable to the situation. Now that the program exists the only thing required to apply it to another PV array is experimental inverter production data from the site. This can be used to determine soiling rate as well as average production values. Once this is accomplished the program is capable of making estimates at the financial break even point for the given situation.

The main issues and challenges associated with developing the cleaning schedule program arise from inaccuracies in measuring the data from the panels and the instability of the weather. First of all, collecting data from the panels will require our group to determine what differences in data are due to the cleaning of the panels and those due to random changes in weather or etc. Furthermore, unpredictable weather could slow down the development of the program as data needs to be collected during different seasons in order to have a fully thought out schedule. We will need to determine the impact of rainfall to be able to accurately estimate how it affects the panel's cleanliness. If this winter does not contain enough rain events, that could prevent this estimate from being completed until further into spring quarter.

- **7. Sustainability**

The only issues facing the completed recommendation will be unanticipated changes to the system. If something were to happen that would drastically increase or decrease the soiling rate over an extended period of time, it could render our program unuseable. Upgrades to the design would come in the form of more personalization and a clean UI, allowing the end user to alter the program assumptions easily and intuitively. The accuracy of our model would be improved with multiple case studies and a longer time frame. The constraint that prevented these upgrades was the lack of time to collect and process data. An organization that can conduct years long studies would be better equipped to improve the model. As climate patterns and ecosystems change over time due to climate change soiling rates and production estimates for a site will change as well. If an area gradually becomes more arid and dusty recommendations many no longer hold true. If data is continually collected and analyzed to ensure model integrity this shouldn't be a problem. More additional work could come in the form of another program to scrape inverter data and synthesize inputs for the original program from this data. This could drastically increase product fidelity and accuracy.

- **8. Ethical**

When taking into account the type of project that we are working on, developing a cleaning schedule for the solar farm, there are certain codes from the IEEE code of ethics that are more relevant to our project. For example, in Code 1, it states that we should comply with sustainable development practices. This is a key concept in our project as we are trying to make the solar farm as efficient as possible, while trying to remain environmentally friendly.

Code 3 from the IEEE code of ethics states that we must be honest and realistic when stating claims off of available data. Again, this ties right to the core of our project as the program we will create will come from the data we collect at the solar farm. It is important that we collect accurate data to create the best possible version of our program. The more accurate and useful our data is, the more accurate and reliable our conclusions from the data can be. We were sure to make assumptions that would not lead users to a situation where the model estimates profit but in reality loss occurs.

Furthermore, Code 7 states that we must properly credit the contributions of others. We have found data about how soiling can affect solar panels efficiency based on different regions and even found a recommended cleaning schedule based on a couple different climate types. These reports can help us to understand our data better and build a more robust model. It is important that when we make our analysis and conclusions based on data cited in these reports as they gave us a foundation to build off of.

Finally, in the making of the schedule, it is also very important that we cause no damage to the property of the solar farm, adhering to Code 9. Damaging the solar farm will undermine the purpose of the project, which is to make the farm more efficient. We will have access to the solar farm in order to collect data and clean the panels as needed so it is important that in the process we make sure not to damage the panels in any way. We aim to leave the solar farm in the same or better state than how we came to it.

- **9. Health and Safety**

Since our project has no hardware there will be no manufacturing or lab design which significantly reduces any possibility of harm. The project is a recommendation rather than a product so there should be no health and safety concerns associated with the product itself. To collect data and clean solar panels, we will need to drive out to the farm and sign a safety waiver to enter. At least two researchers will enter the farm at a time to minimize the potential risk associated with data collection.

- **10. Social and Political**

The largest political issue this project will run into is climate change. Some individuals claim that focusing resources on alternative energy sources is a waste of time and we should be optimizing existing fuel based energy systems, but this can be countered with a simple economic argument rather than a political one. There is nothing inherently bad about planning to make an existing installation more efficient. Our project can help stakeholders achieve energy independence, achieve higher energy production with PV arrays, avoid the corruption of the fossil fuel industry and decrease carbon emissions.

This project's direct stakeholders are solar farms, as they will see the profit directly. It can be argued that everyone on earth is an indirect stakeholder, since transitioning to alternative energy is a process that will benefit us all. This project will be beneficial to all stakeholders, the solar farms will see this benefit though profit while everyone else will see this benefit through curbed emissions.

- **11. Development**

  This project developed a program to predict the most profitable time to clean a solar farm, taking into account weather, soiling rate, and electricity price. The program was able to split costs and profits between two entities to show the potential benefits of cleaning solar panels. An understanding of solar panels, power systems, and economics was needed to analyze and model the data collected. Microsoft Excel was used to process the collected data and determine soiling rates. MATLAB was used to model our project and provide us with the analysis of cleaning the panels on certain days. More data over a longer timeframe would have been ideal to create a more accurate prediction. This program can be improved upon in the future with multiple case studies and the addition of more data from the Gold Tree Solar Farm.

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