Determining a Reliability Factor for Photovoltaics in San Luis Obispo

By

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ABSTRACT

This project will analyze raw photovoltaic (PV) solar panel performance data in order to determine a reliability factor for solar panels in San Luis Obispo. This project is a subset of a larger project being performed by SLO RESCO, which is funded by a grant from the California Energy Commission. Their project will explore the use of solar, wind, geothermal, and biomass renewable resources. The scope of this project is limited to a small section of RESCO’s analysis of solar panel technology and implementation in which a reliability factor will be generated.

The objective is to determine a reliability factor for solar panels for each month of the year while creating an Excel tool to assist with the calculations and organization of information. The analysis of this report involved obtaining one year’s worth of PV performance data, manipulating and interpreting an entire year’s worth of PV performance data, designing and generating an Excel tool to perform the calculations, and finally making conclusions and recommendations. In order to perform the analysis many variables had to be defined, as well as ways to interpret the results such that the desired outputs could be obtained.

From the data and results San Luis Obispo had a capacity factor of 80.94% from May 2009 through April 2010. The reliability was significantly higher in the summer months as compared to winter. The next step for the solar industry should be to develop a more representative capacity factor that is based on the number of hours the sun is out (usually 10-14 hrs) rather than a 24 hour period. This value could generate a lot of interest in the solar industry and eventually could help change people's views and impressions as well.
# TABLE OF CONTENTS

ABSTRACT ...................................................................................................................................................... 2  

TABLE OF FIGURES ......................................................................................................................................... 4  

TABLE OF TABLES ........................................................................................................................................... 4  

INTRODUCTION ............................................................................................................................................... 5  

BACKGROUND .............................................................................................................................................. 7  

LITERATURE REVIEW .................................................................................................................................... 9  

DESIGN ........................................................................................................................................................ 15  

  Problem Statement .................................................................................................................................... 15  

  Activities Required to Complete the Analysis .......................................................................................... 15  

    Step One: Obtain Performance Data .................................................................................................. 16  

    Step Two: Design of Experiment ....................................................................................................... 17  

    Step Three: Design the Excel Tool .................................................................................................... 20  

    Step Four: Analyze Results and Draw Conclusions ........................................................................... 25  

RESULTS ...................................................................................................................................................... 27  

CONCLUSION ............................................................................................................................................... 30  

REFERENCES ................................................................................................................................................ 31  

APPENDICES ................................................................................................................................................ 33
TABLE OF FIGURES
Figure 1: How solar energy works (ACTewAGL education site) ................................................................. 12
Figure 2: Actual performance curve vs. Ideal performance curve .............................................................. 17
Figure 3: Boxplot of each month's Reliability factor .................................................................................. 26

TABLE OF TABLES
Table 1: Raw performance data from REC Solar ......................................................................................... 16
Table 2: Screen shot of Excel Tool .............................................................................................................. 22
Table 3: Summary of Monthly Reliability and Statistical Results ................................................................. 27
Table 4: Raw Performance Data ................................................................................................................. 33
Table 5: Screen shot of Excel tool tables summarizing daily performance statistics and reliability factors
for one month ............................................................................................................................................. 33
Table 6: Screen shot of Excel tool table that summarizes each day of a given month .............................. 33
INTRODUCTION

In recent years there has been a strong push by the US government to reduce our need on fossil fuels for energy and switch to renewable and sustainable energy. There have been independent studies that analyze the potential of wind, solar and water energy in various climates. In order for the future to enjoy the same environmental luxuries we currently have, we need to start implementing and utilizing alternative energy. Relative to fossil fuels and other resources on earth that can be depleted, the sun provides a continuous stream of solar energy. Solar panels are able to capture sunlight and convert it into AC current that can be put into local energy grids which in turn is used by community members.

This senior project is a subset of a larger project sponsored through a grant from the California Energy Commission. SLO RESCO is the ten member team who is exploring the possibility of making San Luis Obispo County completely reliant on renewable energy. This will be achieved using a combination of solar, wind, biomass, and geothermal energy. This project assisted with the solar aspect of their project in which a reliability factor for photovoltaic solar panels will be calculated for systems in San Luis Obispo. The goal of this project is to create a tool that will analyze annual performance data and from that, determine the reliability of solar panels for each month of the year.

Current energy production is reliant on the use of fossil fuels and nuclear generators. Using these current systems requires a lot of time, money, and creates undesired pollution in the atmosphere. Current nuclear power plants generate one billion watts of power which is enough energy to power a city with roughly one million residents. The sun on average delivers the equivalent of 63 million power
plants. We have shown the ability to harness this energy and turn it into useable AC current without giving off any pollution into the atmosphere. It is now time to take the next step in the development of solar panels and harnessing solar energy which is where this report comes into play.

In order to properly perform the analysis and achieve the desired goals various Industrial Engineering techniques will need to be explored and implemented. These analysis techniques consist of: design of experiment, human factors, statistical analysis and design, and computer programming. Design of experiment will be used to determine the proper method for comparing the actual performance data in order to obtain the desired outputs. Human factors will be used to determine a user friendly layout for the software tool as well as incorporating as much automated calculations as possible. There is also a need for statistical analysis and design to determine and generate the necessary statistical outputs that accurately represent the data being analyzed. All of this will be further discussed and analyzed in the methodology and results sections of this report.

The main report will be divided into the following sections: Introduction, Background, Literature Review, Design, Methodology, Results and Conclusion. This comprehensive report is intended to be submitted to Industrial Engineering faculty and the SLO-RESCO team for further review. After extensive analysis this report will provide new information and will help SLO-RESCO with the creation and implementation of future policies for solar panels and utility companies. There will be thorough analysis that can be reviewed in the report to back up how the conclusions and recommendations were reached.
BACKGROUND

Photovoltaic solar systems were first used by the United States government on satellites in outer space back in the 1950's (Energyquest). Since then, the true potential of these systems have been discovered and helped pave the way for modern solar cell systems. This report will further analyze and determine the reliability of energy production from solar cells in San Luis Obispo County, while building a tool that can be used to further analyze other aspects of solar energy.

This topic is just a small aspect of an even larger project that is being completed by a team in San Luis Obispo called SLO-RESCO. RESCO is an acronym that stands for Renewable Energy Secure Communities. The team is working on a project that should ultimately allow San Luis Obispo County to be completely reliant on renewable energy, and move away from our dependency on fossil fuels or nuclear power for electrical needs. The team will be investigating solar, wind, geothermal, and biomass energy sources to accomplish their ultimate goal. The project that is being undertaken by the SLO-RESCO team is being funded by a grant from the California Energy Commission.

During the analysis process, the information will be compared to and fulfill the theory of the "Triple Bottom Line." The Triple Bottom Line takes into account the environment, economy and people. When analyzing the environment, consideration needs to be given to all the materials in the products, the manufacturing process, the installation process, maintenance of the products, and finally ultimate disposal of the product. The goal is to make sure that the environment is not harmed by any means from the use or production of the products that will be used. The next step is to make sure that the product will be profitable for the business or at least cost justified before implementation. Lastly the products should not cause any harm to any humans who are directly affected by the products as well as humans.
all over the world. If all three of these categories are satisfied than the project can be considered sustainable, which is the point of switching to renewable energy.

The SLO-RESCO team will take into account the Triple Bottom Line with strong emphasis on the environment. The goal is to be able to reduce the dependency on fossil fuels and nuclear energy which in turn will reduce CO$_2$ emissions, reduce money spent on the production of electricity using modern methods, and provide endless amounts of energy with little maintenance required. This report will help identify the reliability of energy production in San Luis Obispo County. By determining the reliability of energy production this will help in the future analysis of new capacity factors and loss of load probability. There is some variability in the data due to other variables such as shading, azimuth, pitch, and temperature but analyzing these factors is outside the scope of this project.
LITERATURE REVIEW

The sun has been providing the earth with energy for billions of years, and will continue to do so for billions more. The sun not only provides energy through the light rays it emits that reach the earth, but it also drives wind and waves. With the proper technology, the entire planet could potentially become solely reliant on renewable energy, which would allow us to move away from the use of coal, oil and nuclear energy. Today nuclear power plants generate one billion watts of energy, enough to power a city with a population of one million people. In comparison, the amount of energy delivered by the sun is equivalent to 63 million nuclear power plants (SLO RESCO). Performing extensive and thorough analysis in this field can provide voluminous long-term benefits to all mankind such as: creating more sustainable energy production, lowering CO\textsubscript{2} emissions, and taking advantage of an unlimited energy source. The analysis performed in this report will strictly be covering a small scope of this vast topic. In particular the analysis will be focused on how various factors such as: climate zone, weather, installation, angle of the sun, and other factors, affect the performance of solar panels. In addition, it will also compare the actual and predicted output performance levels of solar panels.

The State of California has released statements claiming that by 2030 it wants one third of its electricity to come from renewable energy. In addition to using a renewable energy that is clean and free, there are other incentives for going green and using solar energy. According to the online website Database of State Incentives for Renewables and Efficiency (DSIRE), the state of California is offering financial incentives through property tax, rebates, loans and production incentives. Utility and other local incentives have also been offered throughout the state. San Luis Obispo is a perfect candidate for utilizing solar energy because the county averages 315 days of sun per year and is located in a Mediterranean climate. All of these factors demonstrate the potential benefits that will yield from
performing a senior project in a field that is receiving a lot of support and promises to have a lasting impact.

The energy from the sun is not delivered in one standard light wave. The electromagnetic spectrum extends well beyond the visible light we observe on a daily basis. There are waves that are shorter than blue light, commonly referred to as the Ultraviolet (UV) range, and there are waves that are longer and slower than red light, known as Infrared (IR) light. Most of the energy comes from the light waves in the middle of the visible spectrum which are observed as green and yellow light. The Ozone layer is responsible for absorbing most of the ultraviolet light emitted by the sun, while the infrared light is absorbed by water vapor and carbon dioxide particles. Most of the sunlight that reaches the earth's atmosphere doesn't reach the ground, instead it is reflected back out into space. Furthermore, much of the sunlight is often scattered within our atmosphere due to interactions between the light waves, gas and dust particles. This scattering is the phenomenon responsible for giving the sky its characteristic blue color. There are various terms that are used to identify the type of light energy that reaches the surface of the earth. The light that hits earth's surface directly without being scattered or reflected is referred to as "direct radiation" or "direct-beam." Scattered sunlight is called "diffuse" radiation, while "albedo" radiation is light that has been reflected off the earth's surface. The sum of direct, diffuse, and albedo radiation is called "Global" radiation.

In order to help measure and quantify some of these terms there are a few standard units in use today. A "Standard Test Condition," also referred to as "One Sun," is defined as 1,000 Watts of energy per square meter at 25 degrees Centigrade which is seen through 1.5 times the thickness of the atmosphere. These conditions, through extensive testing, are the conditions that promote ideal behavior and energy production for solar cells. This information is used when determining ideal current and voltage levels. Kilowatts per square meter (KW/m²) is the standard measurement when looking at
the amount of power per unit area, and is also referred to as incident solar radiation. Kilowatts per square meter can be used whether looking at a given point in time or over a continuous basis. Energy is measured in kilowatt-hours (KWh) as opposed to power which is measured in kilowatts per square meter (KW/m²). A kilowatt-hour is defined as 1000 watts of power delivered for one hour, or any equivalent thereof. For example, it could be 500 watts delivered over two hours, or 2000 watts for a half hour. Lastly energy can be measured in kilowatt-hours per square meter, which measures the amount of energy delivered to a flat square meter surface over a period of time.

There are two commonly used technologies to harness solar energy. The first, and less common method is Concentrating Solar Power Systems (CSP) which can only use direct beam radiation to generate energy. Conversely, the more common method is Non-concentrating Photovoltaic Solar Systems (PV) which uses direct, scattered and reflected sunlight to generate electricity (California Solar Resources). The examination of this report will focus on photovoltaic systems. There are many types of photovoltaic solar cells, but the most common are the following (Solar Cells Technologies):

**Monocrystalline:** these cells are made from the highest grade of crystalline silicon. The silicon is grown as a single crystal in a single plane, and this material acts as the light absorbing semiconductor in the cells and begins the process of generating energy. These cells are large, sliced into wafers, and they have very high efficiency. These panels are considered to be very durable and are estimated to have a useful life of 80 years.

**Polycrystalline:** These wafers are slightly less efficient than monocrystalline, but they are cheaper and less complex to manufacture and therefore are the most commonly used today. There are multiple crystals per ingot and not all crystals are oriented in the same direction reducing the efficiency of the cells.
Amorphous: These silicon cells are a common commercial product but they are less efficient than crystalline silicon wafers. They are cheaper to produce than the crystalline cells but they are also less efficient. To help increase efficiency multiple layers of material may be placed on top of each other to gather the light that penetrates through the top layer. The material lacks orderly structure and therefore the physical properties are often compared to those of glass. Many of these products come with a warranty assuring at least 80% of the initial rated production for 20 years.

Multi-Junction: These consist of multiple layers each designed to capture different parts of the light spectrum (band gap). These products are highly efficient because they are designed to capture the entire light spectrum, but are very costly to produce. These systems are being used primarily in space programs.

All Photovoltaic systems use a relatively simple process to convert solar energy into electricity. The steps are as follows: (1) Sunlight comes down and hits the panels which absorb the photons, silicon is typically used as the semiconducting material. (2) When the light strikes the wafer, the material knocks loose the electrons from the light atoms. (3) Conductors are attached to the positive and negative sides of the semiconducting material which forms a circuit. (4) The electrons, when captured, can be turned into an electric current, aka electricity. This electricity can be used to power any load or put back into the energy grid. The process described can be seen in Figure 1.
Solar cells are rated with conversion efficiencies. The efficiency of a solar cell is measured as the percentage of power from absorbed light which is converted to electrical energy. Factors related to the production of cells that affect the efficiency are: the amount of material required, cost of material and production, time to payback the energy required to manufacture the components, and area required for the solar system. Currently, the top commercial solar cells have efficiencies of roughly 20-21% (Solar Expert). Factors that affect the energy production of Solar PV systems are: time and intermittency of solar power, solar geometry, shading, heat, tracking, and inverters. Right now solar efficiency is really low and there is much talk about how solar energy is intermittent and thus not a reliable sustainable energy source. No studies were found that determine the true reliability of solar panels which is the bases for this project.

Not only can solar energy help produce electricity, they do not consume water so savings in that area are also realized. It is a well known fact that most of California, and many other states in the United States are experiencing significant water shortages. With current energy production thermoelectric power plants are responsible for producing 75% of the electricity used in the United States and water is being used to cool these plants which produced a total of 4,115 terra-watt hours of electricity in 2008 (Global Water Intelligence). On average, these plants use approximately 600 gallons of water per megawatt hour produced. With the implementation of solar panels much of this water can be conserved and/or used elsewhere. Currently, between the residential and commercial sectors in the United States over 200 million metric tons of CO$_2$ are being produced just to heat water through the use of electricity and natural gas. Since solar panels become less efficient at producing electricity as they heat up, one alternative to this problem is to run water through tubes under the panels to both cool the panels. Furthermore, if water isn't readily available, then dry-cooling technologies exist. This would be also help in reducing CO$_2$ emissions and allow more water to be used in other sectors around the country.
A proper analysis of the reliability of solar panels will require the knowledge and use of statistical analysis and design, design of experiment, human factors, and computer programming. Several studies have been performed, which have analyzed the following: economic justification of using solar energy over fossil fuels and other methods currently being employed, potential energy production, collection of raw solar data, meeting state requirements for energy production, and what materials outperform others. This report will analyze the reliability factor of solar panels during each month of the year. Ultimately, the goal is to determine a reliability factor for solar panels in San Luis Obispo county for each month of the year. A tool will be designed in order to properly analyze the information provided, which ideally will generate a reliability factor for any system around the world as well as provide other useful information. Analysis will be performed on the variability and quantity of the electrical output from solar panels. Information management will also be an important aspect of this project to obtain the necessary outputs from over 35,000 rows of raw performance data. This will be addressed through analysis on how frequent data needs to be collected, how the information should be collected and processed, and how many sites need to be evaluated to provide an accurate forecast for the county.

It is the intent of this project to ultimately determine a reliability factor for solar panels while creating a tool that will automatically perform the analysis with minimal effort required by the operator. There is much hope and potential in this new and exciting field. This project has the potential to help reshape how people view and utilize not only the sun, but all renewable and sustainable resources around the world.
DESIGN

This section of the report will go into detail how the project and analysis was approached as well as conducted. There will also be a discussion of the step by step process used to test the design and generate the desired results. It will encompass everything from the initial data collection and everything up to and including analysis of the results.

Before coming up with the design for the analysis, meetings with the RESCO team was required to hone in on a specific problem statement that clearly identified the goal of this project. There were, however, a few limitations when coming up with the problem statement. The RESCO team is trying to analyze and forecast solar performance data for San Luis Obispo County. This presented the challenge of finding raw performance data from a very small sample of systems. From these meetings the following problem statement was developed.

Problem Statement

Determine a reliability factor for photovoltaic solar panels in San Luis Obispo for each month of the year.

After defining the problem, a plan of action was needed to set a timeline for the completion of this project which is described in the next section.

Activities Required to Complete the Analysis

In order to accurately determine a reliability factor raw performance data had to be gathered, a method to analyze the data was required, and a tool to perform the analysis was necessary, generate the tool, and analyze and draw conclusions from the results. The diagram below, depicts the steps taken for this analysis after defining the problem statement.
Step One: Obtain Performance Data

The first step of the process was to obtain one year's worth of performance data for a system in San Luis Obispo. REC Solar was able to provide raw performance data for one of their local systems. This data came in fifteen minute intervals for each day of the year. It contained information about Peak AC Power in kW being produced by each of the two inverters (I₁ and I₂ were the associated variables used in later calculations), a running total of the energy produced to date in terms of kWh for each inverter, the ambient temperature, the solar cell temperature, irradiation, insolation, and local wind speed (see Table 1). Each of the items was placed in the same row with the far left column containing a timestamp with the date and time of day. Not all of these items were required for my project, but it will allow the RESCO team to perform further analysis.

**Table 1: Raw performance data from REC Solar**

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<th>Date</th>
<th>San Luis Obispo System</th>
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<th>Module 2</th>
<th>250W Mono solar</th>
<th>375 degrees</th>
</tr>
</thead>
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</tbody>
</table>
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**Table 1: Raw performance data from REC Solar**
Step Two: Design of Experiment

After obtaining this information the next step was to determine a method to analyze the data that would help determine a reliability factor. In order to obtain the reliability factor it was necessary to determine the total energy being generated by the system during each fifteen minute increment of time. For this project kilowatt hours were used as the unit of comparison instead of kilowatts because it was desired to deal with units of energy being produced by a system rather than the amount of power being generated. These values were summed up and each day was compared to the same fifteen minute increments for an ideal curve from that same month (see Figure ____).

![Figure 2: Actual performance curve vs. Ideal performance curve](image)

Other information, and the corresponding assigned variable in parentheses, that was necessary to complete the analysis was:
• The difference between the ideal curve and actual daily curves (D): The difference between
This was useful in determining the difference in total energy produced by the system on a given
day compared to what an ideal day would generate.
• The percent increase or decrease in kilowatt hours from the previous fifteen minutes (C): This
information helped identify intervals with significant drop offs in energy production. The more
significant drop offs a day had the more unreliable the system was that day.
• Average kilowatt hours produced while the system was generating energy (Tₙ): This value was
used in the scoring system that helps identify the most ideal performing day for each month
which will be discussed later in the report.
• Max kilowatt hours produced in any fifteen minute interval for each day (M): This value was
also used in the scoring system.
• Average difference of kilowatt hours between the ideal curve and a given days actual
performance curve for each time interval (E): This information was not directly used in the
analysis of this report but was an output that will be useful for the RESCO team in their project.
• Total kilowatt hours produced for a day (Kₙ): This value was also compared to the total kilowatt
hours produced by an ideal curve and used in the reliability factor calculation.
• Total kilowatt hours produced by the ideal curve (Kᵢ): This was the baseline and thus any day
with less kilowatt hours was under 100% reliable, and any day producing more energy was
considered over 100% reliable.
• The number of times there was a drop off in kilowatt hours greater than 10% of the previous
interval (O): This value was used in the scoring system to help identify the ideal curve.
• Amount of time the system was producing energy for each day (P): The total kilowatt hours
produced was divided by this to obtain the average kilowatt hours being produced in each
fifteen minute interval of the day.
The next task was to develop a method to determine an ideal curve for each month to use for comparison purposes.

REC Solar was only able to provide a limited sample of performance data, and ideal production curves from online calculators only provide the theoretical total kilowatt hours produced by a system in San Luis Obispo. As a result the conclusion was reached to use the most reliable and best performing day from each month as the Ideal curve for the month. This allowed actual data to be compared to actual data and not have to mix theoretical and actual numbers. Therefore four categories were used and each category was ranked from best to worst performing. The categories used were: Daily max kilowatt hours for a fifteen minute interval (highest max = rank of 1, lowest max = rank of 31), average kilowatt hours produced over a day (same ranking as daily max), number of drop offs greater than 10% (the fewest drop offs = rank of 1, most drop offs = rank of 31), and total kilowatt hours produced for the day (same ranking as daily max and average). The items previously stated are the most pertinent to determining solar reliability because a reliable system should have a relatively high daily max production, relatively high and consistent average kilowatt hours produced, as few drop offs greater than 10% as possible and a large total for kilowatt hours produced.

Each category however has a different level of significance in relation to determining reliability so weights were assigned to each category based on what was believed to be most and least important to reliability. The weights used for this project are as follows: 40% for the number of drop offs greater than 10%, 25% for total kilowatt hours produced, 20% for the average of the daily production, and 15% for the days max kilowatt hours produced in any fifteen minute interval (see table 7 for sample calculations). The weights for each category were discussed and agreed upon after meeting with members of the RESCO team. These weights were used in conjunction with a ranking system for each category where 1 is the best (i.e. greatest max, highest average, least number of drop offs, and most
kilowatt hours produced) and 31 is the worst. When each rank is multiplied by each weight the raw score is then added up for each day of the month. The day that had the lowest total score for the month was then used as the ideal data to compare with the actual data for that same month.

EX: May 9th, 2009: 1st (Avg), 2nd (Max), 6th (# of drop offs), 1st (total energy produced)

Weights: 20% Average, 15% Max, 40% # of drop offs, 25% total energy produced

Raw Score: (1 x .2) + (2 x .15) + (6 x .4) + (1 x .25) = 3.15

For each month the ideal data served as the standard for the amount of kilowatt hours that should be produced for each day of the month. Therefore when conducting the analysis, if any given day matched the total energy output of the ideal data, the system is said to be 100% reliable. If the total energy did not match the ideal curve, the total kilowatt hours generated by that day was divided by the ideal energy produced. This number represents the percentage of total energy produced when compared to an ideal day. This percentage was calculated for all 365 days as well and analyzed on a monthly basis. For each month the average, maximum, minimum, and range were all calculated. This provided monthly intervals where the averages represent the reliability of solar energy for that month. This data will then be used to make box plots for each month showing a range for the reliability with the mean representing the calculated reliability factor for the month.

**Step Three: Design the Excel Tool**

After defining how to attack the problem and properly analyze the data, the tool had to be created to perform the analysis. The purpose for creating a tool that performs the calculations it will save time for future users. REC Solar already has software in place that put all of the data in an organized Excel sheet containing important performance data in fifteen minute increments. The tool is used to put all of this data into one sheet and then into twelve other sheets, one for each month. The cells in each monthly sheet reference the main sheet to pull out all the data corresponding to the proper
time stamp. In order to perform the necessary analysis though, a few more columns, as well as tables, needed to be added to the file. It was necessary to determine:

- Total energy produced by the system for the day: \( K_A = I_1 + I_2 \)
- Total energy produced by the system on an ideal day from the same month: \( K_i = I_1 + I_2 \) where the values of \( I_1 \) and \( I_2 \) are for the ideal day determined by the scoring system
- The difference between total energy produced on an actual day versus the ideal day: \( D = K_i - K_A \)
- The percent increase or decrease in energy produced between consecutive time intervals: \( C = \frac{(k_{n+1} - k_n)}{k_n} \) where \( k_n \) represents the kilowatt hours produced for a given 15 minute interval
- How many hours a day the system was producing energy: \( H_p = \frac{P}{4} \)

Each of the items listed above was put in its own column and calculated for each time interval for the entire year's worth of data. The way total energy produced by the system for a day was calculated was by looking at \( I_1 \) and \( I_2 \), which represent the running totals of total kilowatt hours produced for Inverter 1 and 2 respectively. The incremental change from one cell to the next one below was calculated by subtracting the previous cell value from the next. A sample of the code for this calculation is: \( K_A = (I_{2(n+1)} - I_{2(n)}) + (I_{1(n+1)} - I_{1(n)}) \). This provided kilowatt hours produced for every fifteen minutes and these values were summed up for the entire day. Total energy produced by the system was calculated using the same methodology as calculating total energy produced for a day. The value for each fifteen minute interval was then placed in for the values of \( K_A \) in the Excel tool. The difference between actual energy and ideal energy produced was calculated by subtracting \( K_A \) from column \( K_i \) and these values were then stored for each time interval in every row for the values of \( D \). An example of the calculation is: \( D(45) = (K_A(45) - K_i(45)) \). The values in the parentheses by each variable indicates the row the calculation is being performed for. The percent increase or decrease was calculated by subtracting the value from the previous time interval in \( K_A(n) \) from the value corresponding to the next time interval.
$K_{A(n+1)}$, which was then divided by the previous time interval. An example of this calculation is:

$$C(45) = \text{IF}(K_{A}(44) = 0, \text{""}, (\text{ABS}(K_{A}(44) - K_{A}(45))/K_{A}(44)))$$.

The IF function was used in order to only show increases and decreases in production only during the hours of production and rows corresponding to night hours will be blank. In order to calculate the number of hours the system was producing energy for a day an IF function was used again. The solution was found by looking at column L and if there was a value of zero, then no energy was being generated and if there was a value greater than zero, energy was being produced. Column R was used to place a zero, corresponding to no energy being produced, or a one which signifies energy was being produced (variable = Q). The equation used in Excel was

$$Q(13) = \text{IF}(K_{A}(13) > 0, 1, 0)$$,

and this equation was identical for all rows using the respective L and R cells for calculations. Q was then summed up for the entire day and divided by four to identify the total hours of production.

After determining these values, tables were designed to analyze and summarize the data for each month. A screen shot of the tool that shows the calculations can be seen in Table 2.

Table 2: Screen shot of Excel Tool

<table>
<thead>
<tr>
<th>Time Field Name</th>
<th>Total Energy Generated kWh</th>
<th>Peak AC Power kW</th>
<th>Total Energy Generated kWh</th>
<th>Peak AC Power kW</th>
<th>Ambient Temp °C</th>
<th>Irradiation W/m²</th>
<th>Wind speed mph</th>
<th>Energy Generated kWh</th>
<th>Idea Energy Generated kWh</th>
<th>Energy Difference (Idea-Real) kWh</th>
<th>Percent Change</th>
<th>Colli Over Ambient Temp °C</th>
<th>Min units of production</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/1/2009 00:00</td>
<td>150771</td>
<td>0</td>
<td>158500</td>
<td>0</td>
<td>8.2</td>
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<tr>
<td>12/1/2009 23:00</td>
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<td>0.7</td>
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</tbody>
</table>
This information was then used in calculations to generate the information in Table 4 in the Appendix.
The information in this table shows a comparison between the average of every day of the month compared to the data from the ideal day for the month. The table also shows the reliability factor (variable = R), in the bottom right cell which is represented as a percentage. The equation used for this calculation was $R(6) = (T_A(6))/(T_I(6))$. Table 4 in the appendix also shows the maximum, minimum, standard deviation, range and average of the reliability factor for each day of the month. The last item to create in the tool was a table summarizing that aggregated the information from the green table in Table 4 (see appendix) from each month. This allows the user to input all the raw data on one sheet and then with one click the summary sheet can be pulled up showing the reliability factors for each month can be easily identified. In order for this to happen, it was required to have the cells of the summary table reference the cells that contained the summary information in each sheet. If more detail is desired by the user, there is a sheet specifically created for each month which allows for daily or even hourly analysis.

One more table (see table 5 in the appendix) was still required to summarize the information from each day so that these values would in turn be aggregated and averaged to provide monthly data. This table provided the following information:

- Average kilowatt hours produced during each fifteen minute interval: This value was determined by summing up the total kilowatt hours produced for a day and then divided by the amount of time the system was producing energy.
- Daily maximum kilowatt hours produced for any time interval: This value was used during the scoring of each day to help determine the ideal day for each month.
- Daily minimum kilowatt hours produced for any time interval (typically zero): This value was not used in any calculations but is a statistic that may prove useful in for the RESCO project.
• Average difference kilowatt hours between the ideal and actual data for each time interval (X): For every fifteen minute interval of every day the difference in kilowatt hours produced on an actual day was compared to the ideal day and the difference was stored in another column. This information was not directly used but interesting to see on average for the day how much it was under producing compared to an ideal day.

• Actual total kilowatt hours produced for a day: This was determined by summing up the kilowatt hours produced by the system for each fifteen minute interval.

• Ideal total kilowatt hours produced for a day: This was determined in the same manner as the actual kilowatt hours produced but the ideal day was determined through the scoring system.

• Ratio of Actual kilowatt hours produced/Ideal kilowatt hours produced: This ratio served as the reliability factor for each day and then the average for the month was taken to determine the reliability factor for the month.

• Number of time intervals with drop offs in production of 10% or more: This was needed because it was one of the categories in the scoring system. This was used because a reliable day should have as few significant drop offs as possible.

• Number of time intervals with energy production: This information was used in calculating the number of hours the system was producing energy. The number of intervals was summed up and then divided by four to change the units into hours.

In order to calculate the average kilowatt hours produced, the total kilowatt hours for the day was divided by the number of fifteen minute intervals with energy production. An example equation for this is $T_{A}(9) = E(9)/P(9)$. To calculate the daily maximum kilowatt hours produced, the MAX function in Excel was used and it took the max from the array for each day’s worth of data. For example, the max for December 2nd, 2009 was found with $M(10) = \text{MAX}(K_{A}(108):K_{A}(203))$. The minimum for each day was found using the same technique only the MIN function was used to analyze the same array. The next
The item to calculate was the average difference between the actual and ideal performance data. To do this the average of D was taken but only when the value was non zero. This is because it was only necessary to know the average difference during the hours of production. If a relatively large quantity of zeroes are averaged in then this would distort the desired number. To avoid this problem the AVERAGEIF function in Excel was used, for example, cell X(10)(avg for Dec 2nd) =AVERAGEIF(D(108):D(203), "<>0").

Calculating the actual and ideal total kilowatt hours produced used the same method as discussed earlier in the report. The ratio of these two value was calculated by dividing the actual production by total production and stored as a percentage. To calculate the number of drop offs greater than 10% a column was added and used the same method as number of time intervals with production where zero represents no and one is yes. The specific function input into the cell was =IF(AND(C(13)>10%, K(12)-K(13)>0), 1, 0). The first argument checks for the drop off greater than 10% and the second argument checks for whether energy was being produced or not. The second argument is there only because of the occasional occurrence of negative production during the night. The number of time intervals with production was calculated by summing up column R for each day.

After setting up all the equations and cell references the next step was to input the raw data, analyze the results, and draw conclusions.

**Step Four: Analyze Results and Draw Conclusions**

The last step of the experiment was to identify and analyze the results, as well as draw conclusions about the problem statement. This required interpretation of numerical results and did they match or differ from what was expected. It was beneficial to have one table summarizing the main results from the Excel tool however it was very quantitative and not so much qualitative or visual. To generate a complete picture of the results, Minitab was used to generate box plots for each month. From a quick glance at the graph it was easy to identify the best performing months as well as the most reliable months over an entire year which can be seen in Figure ____ on the next page.
This part of the experiment was straightforward and required a lot of critical thinking about whether the results made sense, and did they differ from the initial expectations. More of the results and how conclusions were made will be discussed in the Results and Conclusions sections of this report.

Figure 3: Boxplot of each month’s Reliability factor
RESULTS

This section of the report will summarize and present all the resulting data from the analysis.

Since a factor like this has never been calculated before for a system in San Luis Obispo, there was no previously existing base for comparison. Therefore the expectations for the resulting Reliability factors were somewhat low with a trend of less reliability during the winter and spring, with more reliability during the summer and fall months. Surprisingly, the actual results shown in Table 1 below, were fairly close to the expectations. The same numbers can be seen on a Box plot graph in Figure 2 in the Appendix.

Table 3: Summary of Monthly Reliability and Statistical Results

<table>
<thead>
<tr>
<th>Month</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
<th>Annual Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>84.4%</td>
<td>73.33%</td>
<td>82.0%</td>
<td>83.0%</td>
<td>81.15%</td>
<td>85.02%</td>
<td>92.5%</td>
<td>91.58%</td>
<td>87.90%</td>
<td>82.73%</td>
<td>80.40%</td>
<td>69.14%</td>
<td>80.94%</td>
</tr>
<tr>
<td>Max</td>
<td>100.67%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
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</tr>
<tr>
<td>Std. Dev.</td>
<td>28.09%</td>
<td>25.27%</td>
<td>19.31%</td>
<td>20.84%</td>
<td>13.45%</td>
<td>15.83%</td>
<td>7.07%</td>
<td>14.97%</td>
<td>6.79%</td>
<td>21.43%</td>
<td>17.01%</td>
<td>29.52%</td>
<td>18.47%</td>
</tr>
<tr>
<td>Range</td>
<td>96.21%</td>
<td>81.72%</td>
<td>82.58%</td>
<td>79.51%</td>
<td>55.42%</td>
<td>70.42%</td>
<td>35.55%</td>
<td>81.67%</td>
<td>43.28%</td>
<td>98.05%</td>
<td>72.98%</td>
<td>98.18%</td>
<td>74.78%</td>
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<tr>
<td>Reliability</td>
<td>64.40%</td>
<td>67.47%</td>
<td>63.06%</td>
<td>73.33%</td>
<td>81.15%</td>
<td>85.02%</td>
<td>92.5%</td>
<td>91.58%</td>
<td>87.90%</td>
<td>82.73%</td>
<td>80.40%</td>
<td>69.14%</td>
<td>80.94%</td>
</tr>
</tbody>
</table>

From Table 3 above, it can be seen that the months of March, May, June, July, August, September, October and November all had reliabilities over 80%, while April was just under 80% and January, February, and December were significantly less. This confirmed the initial thoughts that Summer and Fall were significantly more reliable than Winter and Spring. The design therefore appears to be both accurate and valid. It is known however that clouds, shading, pitch, and azimuth all affect the productivity of solar panels which was not examined in this report. Each factor would require individual analysis as well as the interactions but more research should be done on the affect of these factors on photovoltaic systems. If one of these factors proves to be significant, it may be possible to take certain steps to improve solar panel performance and would also increase the reliability with respect to the definition provided in this report.
There were a few unusual conditions that arose throughout the analysis process. First it is important to make sure that before using the tool provided, the user should make sure they have an entire year’s worth of data with no gaps, such as missing data or timestamps. During the analysis a few rows of data were blank, but it was proven that energy was being produced. This meant that for some reason the system did not properly log and save the data for that interval. As a result linear interpolation was used to fill in the blank cells in Excel to conduct the analysis. When the cells were blank, values were being returned such as a minimum energy output of -523,062 kWh. After inputting the values from the linear interpolation, the value of the cell was recalculated and correctly replaced by 0 kWh (the true minimum for any day). Another unusual condition that arose was on select days throughout the year there was at most one fifteen minute interval that had negative energy production. Initially, it was unclear how to interpret this value. After talking with an employee at REC Solar, it was discovered that this was due to the fact the system was running through a self check and diagnostic to make sure everything was running properly. Therefore the system had to use energy when none was being produced and therefore it took the energy from the grid which was typically only .1 kilowatts. From this it was determined to just leave the data in the analysis.

Based on the results obtained in this report, there is a lot of room for improvement for solar panel reliability. In order to move forward with this however, a lot of resources need to be devoted to this problem. It will require large quantities of actual production data from many systems to establish a base line. A lot of effort will then need to be put into finding new methods to counter-act the factors that are found to have a significant impact on the production of energy. Hopefully the tool generated from this project will be used to help generate a true capacity fact as well. It would be a lot more beneficial to determine a capacity factor for solar panels based on the amount of hours the sun is out each day, rather than based on a 24 hour cycle. This would be more representative of how well solar panels perform because the sun is usually out for 10-14 hours a day in San Luis Obispo. Having a
capacity factor when the system cannot produce energy half of the time only lowers the capacity factor which can turn away potential investors. A higher capacity factor could generate more interest in this field and establish a more representative present state. The tool can also be used in the future to help determine ideal production curves for each month of the year in any city around the world. It would require vast quantities of actual performance data but would be beneficial in determining government rebates and even forecasting energy production for any location.
CONCLUSION

Knowing the reliability factor for each month in San Luis Obispo is a good starting point but has lead to many more questions. There are many factors involved in solar panel reliability and effectiveness that were not considered in this report. The solution found will help establish future policies with regards to solar energy as well as set a good starting point for future projects. The most important output from this project is knowing the reliability of solar panels for each month in San Luis Obispo. The theory of using actual performance data in comparison to a specified ideal day turned out to be a successful method for this study. It is evident that there is a lot of potential for solar energy in the future, however to make it a reliable energy source will take some extra work.

This project for the most part moved along very smoothly. There were a few bumps along the way and provided valuable lessons for the future. In the beginning there was a lot of time spent trying to define a problem statement without having any performance data. Next time, it would be beneficial to make a problem statement, obtain the data, and then revisit the problem statement to make sure the solution can be found from the data. There were many revisions made to the problem statement both prior to and after obtaining the data. If time was set aside to strictly determine the feasibility of the problem statement, much time could have been saved and better spent performing analysis.

Based on the results of this project, I would recommend first generating a more accurate capacity factor for solar panels. This value alone has the potential to reshape people's view solar energy and may lead to large investments in this technology in the future.
REFERENCES


Database of State Incentives for Renewables and Efficiency http://www.dsireusa.org/summarytables/finre.cfm


Herig, Christy. "Using Photovoltaics to Preserve California’s Electricity Capacity Reserves" National Renewable Energy Laboratory, Co. Sep 2001


REC Solar, provided Solar performance data for analysis
San Luis Obispo County Facts and Figures
http://www.sanluisobispocounty.com/media/facts-figures

Solar Energy Report (unpublished report by SLO RESCO team)

APPENDICES

Table 4: Raw Performance Data

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Table 5: Screen shot of Excel tool tables summarizing daily performance statistics and reliability factors for one month

Table 6: Screen shot of Excel tool table that summarizes each day of a given month
Table 7: Daily Ranks and Scores

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