POWERING CRAWFORD HOUSE WITH

SOLAR ENERGY

A Report of a Senior Study

by

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ABSTRACT

While the technology for solar panels has existed since 1954, these machines are not widely implemented, especially in this region of Tennessee. Usually, solar panels are imagined as topping sprawling factories or Floridian beach houses, but the technology may be implemented in many areas to help business or homes reduce their electricity bills or contribute to a more environmentally friendly future. One such example is the 150-year-old headquarters of Mountain Challenge, Crawford House. After a decade of using a solar array to supplement their electricity usage, Mountain Challenge wishes to upgrade their solar energy system to allow the house to run completely on solar energy. To determine what equipment needs to be purchased, we analyzed data collected by Mountain Challenge over the last decade to determine a mean annual energy consumption as well as a mean annual solar energy production. We found that Mountain Challenge should increase their solar production by a factor of 2.74 and purchase a battery pack of 50 kWh to achieve their goal. An example system upgrade that accomplishes this would cost Mountain Challenge $18,442 and would take approximately 11.45 years for this system to pay for itself.

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CHAPTER I

1.1 INTRODUCTION

Mountain Challenge was the brainchild of Bruce Guillaume. The original goal, which still reigns true today, was to provide safe, high-quality, outdoor experiences designed to change the world one person at a time. The way the company achieves this goal has changed over time, and in recent years has included sustainability education and practices. Some of the practices are behavioral, focusing on reducing waste and promoting recycling. Many other of these sustainable practices, however, have centered around Mountain Challenge's headquarters, Crawford House.

The 150-year-old building has seen many improvements, including more energy-efficient windows, HVAC system, and roofing. The building became certified by the US Green Building Council as "Gold Certified" for Leadership in Energy and Environmental Design (LEED) in 2013, and in 2012, the company installed a solar panel to help power the building (Guillaume, n.d.). It is no surprise, then, that Mountain Challenge is still finding new ways to reduce its environmental impact while supporting local communities.

In 2021, a panel of Maryville College faculty and staff certified the building as carbon neutral. As part of Mountain Challenge's presentation to the board on April 13th, 2021, the organization promised to strive towards a building run entirely on solar energy. This report is a direct result of that promise. We will detail the process by which we determined what changes need to be made to the existing solar energy system for Crawford House to run entirely on Solar Energy and conclude with a recommendation of these changes.

1.2 OVERVIEW OF PROCESS

Mountain Challenge has been gathering data on Crawford House's energy use over the last ten years. These data include the amount of energy purchased from the grid in kilowatt-hours, defined here as 'electricity purchased', dating back to January 2009 and the amount of solar energy used in kilowatt-hours, defined here as 'solar consumed', since the solar panel's installation in February 2012. They also know the number of kilowatt-hours generated by the solar panel that were returned to the grid, defined here as 'solar returned', but only since February 2022. Using the available data, we approximated the total electricity used by Crawford House, defined here as 'electricity consumed' and the total solar energy production, defined as 'solar produced'. The difference between electricity consumed and solar produced allowed us to estimate how much more electricity would need to be generated by solar technology to ensure Crawford House can be powered completely by solar energy. Upon completing the analysis, we decided that for Mountain Challenge to reach its goals they will need to install a battery to store electricity generated by the solar panels. We estimate the expected size of the battery based on the recommendations of a local solar provider. Finally, we suggest some sample equipment which should be able to meet the goals laid out in this report. This example is used to illustrate one way to meet the goal and how long it would take for Mountain Challenge to recoup the money spent on these panels through electric bill savings.

CHAPTER II

2.1 TOTAL ELECTRICITY CONSUMPTION

As previously stated, the electricity purchased does not reflect the total energy consumed by Crawford House. To determine the total annual electricity consumed (E_c), we add solar consumed (S_c) to electricity purchased (E_p) every year from 2013 to 2022.

$$\boldsymbol{E_c = S_c + E_p} \qquad \textit{Equation 1}$$

This represents the amount of electricity produced by the solar panel that Crawford House used and the amount of electricity that was pulled off the grid. Table 1 summarizes the data and calculated electricity consumed for 2013-2022.

Table 1: Electricity Purchased, Solar Consumed, and Electricity Consumed (in kWh) 2013-2022

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Electricity Purchased	7296	9181	10918	10311	8857	9962	19102	14029	5266	5119
Solar Consumed	3938	4024	3680	4090	3957	3613	3908	3785	3992	4122
Electricity Consumed	11234	13205	14598	14401	12814	13575	23010	17814	9258	9241

2.2 TOTAL SOLAR PRODUCTION

Crawford house does not consume all the solar energy produced by the solar panel; each month they send a portion of that energy back into the grid, defined here as 'solar returned.' Mountain Challenge wants to store all the electricity that the new system will produce, so to estimate the solar produced, we use data from 2022 to approximate the solar produced of previous years. Table 2 displays the amount of solar consumed by Crawford House, the amount returned into the grid, and the ratio of solar returned over the solar consumed in the year 2022.

Table 2: Solar Consumed, Solar Returned, and ratio of Solar Returned/ Solar Consumed (in kWh) for 2022

	Solar Consumed	Solar Returned	Solar Returned\ Solar Consumed
Jan	212		
Feb	250	81	0.324
March	264	95	0.359848
April	410	199	0.485366
May	380	178	0.468421
June	404	215	0.532178
July	410	153	0.373171
Aug	365	153	0.419178
Sept	397	215	0.541562
Oct	380	227	0.597368
Nov	375	272	0.725333
Dec	275	144	0.523636

It is worth noting that we considered splitting the data into two groups: 'heating season' and 'cooling season.' Heating season is defined as the months from November to May, and cooling season is defined as the months from June to October. We thought there was value to this, since the mean and standard deviation of solar returned/ solar consumed ratio is different between these two sets. However, the standard error of the annual data set is smaller than either the heating season or cooling season group, as displayed in Table 3 so we decided to abandon this strategy.

Table 3: Mean, standard deviation, and standard error of the heating season , cooling season, and annual Solar Returned/ Solar Consumed ratios for 2022

	Heating	Cooling	Annual
Mean	0.481	0.493	0.486
Standard Deviation	0.142	0.093	0.117
Standard Error	0.058	0.042	0.035

To generate a 95% confidence interval, two standard deviations were added to and subtracted from the mean annual solar returned/ solar consumed ratio. Table 4 shows the lower and upper bounds of this interval.

Table 4: 95% confidence interval for annual ratio of Solar Returned to Solar Consumed.

	Lower Bound	Upper Bound
Annual	0.253	0.720

To create a 95% confidence interval for solar produced for each year from 2013 to 2022, we computed a solar produced lower bound (S_{pl}) and solar produced upper bound (S_{pu}). To calculate S_{pl}, the lower bound of the solar returned / solar produced ratio (L) is multiplied by the solar consumed (S_c) then added to S_c. Similarly, to calculate S_{pu}, the upper bound of the solar returned / solar produced ratio (U) is multiplied by the solar consumed (S_c) then added to S_c.

$$\boldsymbol{S_{pl} = S_c + L\,(S_c)}$$ ***Equation 2***

$$\boldsymbol{S_{pu} = S_c + U\,(S_c)}$$ ***Equation 3***

Table 5 summarizes the results of carrying out this calculation for every year from 2013 to 2022. ‘Lower’ is the lower bound of the 95% confidence interval for annual solar produced while ‘Upper’ is the upper bound of the 95% confidence interval.

Table 5: 95% confidence interval for annual Solar Produced

	Lower Bound	Upper Bound
2013	4935	6772
2014	5043	6920
2015	4612	6328
2016	5125	7033
2017	4959	6804
2018	4528	6213
2019	4897	6720
2020	4743	6509
2021	5003	6865
2022	5165	7088

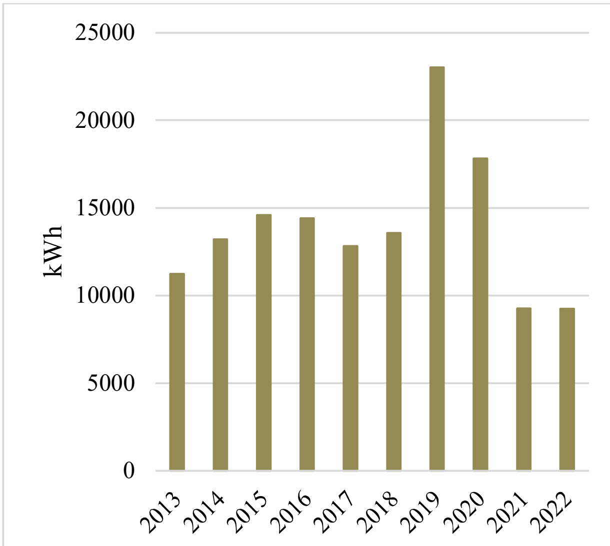
As a result of the calculations of this section and the last, we had an estimate of how much electricity Crawford House was consuming and how much it was producing via its solar panel between 2013 and 2022. In the next section we compute how much more electricity will need to be produced by the new system.

2.3 ESTIMATING ADDITIONAL SOLAR ENERGY NEEDED

To determine how many more kilowatt-hours need to be generated by the new system, we compared solar consumption to solar production. However, before we compared the two, we had to confront an outlier in our data. The year 2019 showed uncharacteristically high electricity consumption during November and December that carried over into January of 2020. The total electricity consumed was so much greater than the rest of the annual totals that we needed to investigate it further. We considered whether a very cold winter would have caused this spike in energy, but data from the National Oceanic and Atmospheric Administration shows that the winter of 2019-2020 was warmer than average (NOAA, 2020). It may be the case that the behaviors of

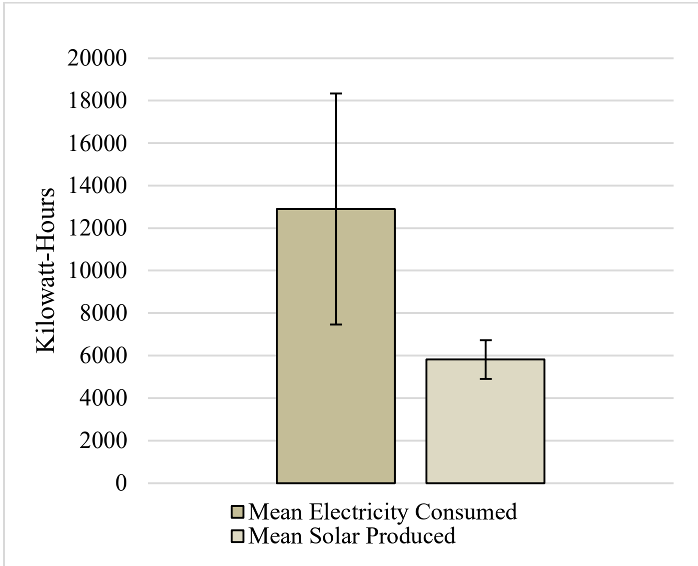
Mountain Challenge staff lead to this spike of electricity consumption. Therefore, we determined it was an outlier and eliminated it from the calculation of mean annual consumption. Figure 1 displays the annual electricity consumed along with the 2019 spike.

Figure 1: Annual Electricity consumed by Crawford House 2013-2022



Thus, the mean (12,904 kWh), upper bound (18,348 kWh), and lower bound (kWh) for annual electricity consumed were calculated without the year 2019. We also calculated the mean solar produced (5,813 kWh) along with a corresponding 95% confidence interval with upper and lower bound of 6,725 kWh and 4,901 kWh. Figure 2 summarizes these calculations.

Figure 2: Mean Annual Electricity Purchased and Solar Produced (2012-2022)



There is a 95% chance that the true mean for electricity consumed falls between its computed lower and upper bound. Similarly, there is a 95% chance that the true mean for solar produced falls between its computed lower and upper bounds. Assuming independence, there is a 0.0625% chance that the true mean of electricity consumed is greater than the upper bound and the true mean of solar produced is less than the lower bound. The difference between the lower bound of solar produced and the upper bound of electricity consumed was 13,447 kWh which is 2.74 times the lower bound of the 95% confidence interval for production. Therefore, we recommend that Crawford House increase its solar produced by up to a factor of 2.74.

2.4 BATTERY SIZE

The calculations above assume that Crawford House will be able to use all of the solar energy produced by the panels. To do this, the house must have the capacity to store excess energy for use later, a capability they don't currently have. For this reason a battery must be added to the current system. Per the recommendations of a local solar installer, we estimated the necessary size of the battery by calculating the mean daily electricity consumed (Bussell, 2023). Using the mean annual electricity consumed, we calculated the number of kilowatt-hours consumed in a 24-hour period using the following formula for mean daily electricity consumed (μ_{CD}) by inputting the mean annual electricity consumption (μ_{CA}).

$$\boldsymbol{\mu_{CD}} = \frac{(\boldsymbol{\mu_{CA}})(\mathbf{24})}{(\mathbf{8765.82})}$$ ***Equation 4***

A similar formula was used to calculate the standard deviation. This formula is shown below where σ_{CD} represents the standard deviation of daily electricity consumed and σ_{CA} represents standard deviation of annual electricity consumed.

$$\boldsymbol{\sigma_{CD}} = \frac{(\boldsymbol{\sigma_{CA}})(\mathbf{24})}{(\mathbf{8765.82})}$$ ***Equation 5***

The calculated mean is 35.33 kWh with a standard deviation of 7.45 kWh and the upper bound of the 95% confidence interval is 50.24 kWh. Therefore, we advise Mountain Challenge to purchase a battery of approximately 50 kWh.

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CHAPTER III

3.1 POTENTIAL EQUIPMENT

We have approximated how many more kWh Crawford House must produce as well as the size for a potential battery. When considering the cost of a new solar energy system, three major expenditures must be considered: solar panels, inverters, and a battery pack. What follows serves as an example, and we suggest Mountain Challenge needs to contact and get a quote from a solar installer before attempting to purchase or install any equipment.

Crawford House currently has ten 240-Watt Solar Panels, so to increase the power output by a factor of 2.74, we multiplied the current maximum power output by 2.74. After doing this, we find that the new system must be rated at approximately 6576 Watts, including the ten existing 240-Watt solar panels. Thus, the new panels must have a power output of approximately 4176 Watts. Ten JA Solar 410-Watt solar panels would achieve this with a total cost of $2,700 (Solaris, n.d.).

Each panel added will need one micro-inverter per panel that must be compatible with a 410-Watt solar panel. For example, the IQ8+ Microinverter would be able to handle the wattage of this panel. Ten of these will cost approximately $1,890 (Enphase, n.d.).

Finally, Mountain Challenge must purchase a battery pack. An example of a battery pack that would function is the Crown 48000 watt-hour Battery Bank. This bank has a cost of $13,852 (Unbounded Solar, 2020).

The price for all this equipment would be approximately $18,442. Since this system will save Mountain Challenge money on their electricity bill, this purchase will end up paying for itself at some point. In the next section we calculate how long it will take for Mountain Challenge to recoup the money they spend on this solar energy system through savings on their electric bill.

3.2 BREAK EVEN POINT

To determine how long it will take for Mountain Challenge's new system to pay for itself though electric bill savings, we performed a simple calculation. The price per kWh, according to the city of Maryville's website, is $0.12482 (City of Maryville, 2022). Since we know the mean Electricity Consumed, we multiply the price per kWh by the annual Electricity consumed to determine how much money Mountain Challenge will save annually, since it will be generating this electricity through Crawford House's solar panels instead of purchasing it from the city of Maryville. When the cost of the new solar energy system is divided by the money saved per year, we find that it will take 11.45 years for the solar energy system to pay for itself. Equations 6 and 7 describe this process.

$$\frac{\$0.12482}{\text{kWh}} * \frac{12,904\ \text{kWh}}{\text{year}} = \$1,610.68\ \text{per year} \qquad \textit{Equation 6}$$

$$\$18,442 * \frac{\text{year}}{\$1,610.68} = 11.45 \text{ years} \quad \textit{Equation 7}$$

While the equipment price used is an example, and the actual cost of a new solar energy system could be lower or higher, the process detailed in this section may be applied to a variety of potential solar energy systems in order to determine how long it will take for the new solar energy system to pay for itself.

CHAPTER IV

4.1 CONCLUSION

This report describes the process of how we determined what type of solar energy system must be implemented at Crawford House in order for it to run independent from the grid. It is our recommendation that Mountain Challenge increase the solar production of Crawford House by a factor of 2.74 and purchase a battery pack of approximately 50 kWh. An example of equipment that could meet this demand would cost about $18,442, and it would take 11.45 years for the system to pay for itself though saving to Mountain Challenge's electricity bill. Mountain Challenge should consult a solar provider for an official quote on the price of a system.

4.2 LIMITATIONS AND FURTHER RESEARCH

There are some limitations to this work, the first of which stems from limited data. Collecting more data on how much electricity Mountain Challenge returns to the grid would help to create a more reliable estimate of electricity consumed and solar produced. Also, more data points may allow a future researcher to separate data into a heating season and cooling season since electricity consumed and solar produced tend to be greater in the cooling season or perform other, more refined data analysis. Such an analysis can help refine the recommendations to determine a cost/benefit for different amounts of battery storage capability. The current estimate is meant to guarantee that no energy from the grid will be needed, however, it may be more cost-effective and ecologically sound to set the battery capacity somewhat lower. Perhaps the largest factor limiting this study is that it does not reflect any changes in equipment Mountain Challenge may make to Crawford House. If Mountain Challenge adds large appliances or switches to an electric heat pump to heat the house in the winter, the house will consume more electricity than this report accounts for.

If a future researcher can determine how many kWh an appliance would consume in a given period of time, those kWh could be added to the mean consumption detailed in this report. This report lays a foundation that may be built upon for numerous years, allowing Mountain Challenge to continuously monitor and calculate what they need to do to stay independent of the grid and continue to meet their sustainability goals for years to come.

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APPENDIX A: DEFINITIONS

Electricity Purchased:	The amount of electricity (in Kilowatt Hours) Crawford House used that was bought from the city of Maryville off the power grid
Solar Produced:	The estimated amount of electricity (in Kilowatt Hours) generated by the solar array currently at Crawford House
Solar Consumed:	The amount of solar electricity produced (in Kilowatt Hours) used by Crawford House
Solar Returned:	The amount of solar electricity produced (in Kilowatt Hours) not used by Crawford House and sent back into the grid.
Electricity Consumed:	The total amount of electricity (in Kilowatt Hours) used by Crawford House. Calculated by adding Electricity Produced and Solar Consumed
Heating Season:	The months that Crawford House needs to be heated, corresponding to the months from November to May. During these months natural gas is used to heat the house.
Cooling Season:	The months that Crawford House does not need to be heated, corresponding mostly to the months from June to October. Categorized by the months where natural gas is not needed to heat the house.