CEE 5052 Project in Environmental Engineering

Spring 2024 Project Final Report:

Solar PV Relocation

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Advisor’s Introduction

As faculty member in the School of Civil & Environmental Engineering at Cornell University and advisor to the project team, I am pleased to write this introduction to the following study on solar PV (photovoltaic) relocation. This study represents an original opportunity to examine the possibility of redeploying a rooftop solar array currently in active use on the Cornell campus as a ground-mounted system, including examination of estimated output and economic cost. Students on the project team completed this project to meet the design project requirement that is part of the Master of Engineering (M.Eng) degree in environmental engineering. I would like to thank Sarah Carson from the Cornell University Office of Energy and Sustainability, as well as all other Cornell staff who contributed, for their support for this project. While this input is gratefully acknowledged, the content of this report does not in any way represent official Cornell policy, and responsibility for any and all errors and omissions rests with the team and with me as advisor.

Executive summary

This report outlines a crucial initiative aimed at advancing Cornell University's Climate Action Plan (CAP) by developing a strategy to relocate the photovoltaic array from the roof of the HEB building to the former coal pile site near the Central Heating Plant. This endeavor reflects Cornell's dedication to sustainability and renewable energy integration. Through thorough research and analysis, including assessments of space utilization, support infrastructure, and energy generation enhancements, the project has identified optimal solutions to propel the university toward its carbon-neutral goals. Notably, a detailed comparison of tilt angle systems indicates that the horizontal tilted single-axis tracking system offers the most promising results, aligning seamlessly with Cornell's sustainability objectives. Analysis of estimates of the potential output from the 76-kW array once moved to the new site revealed values between 67.5 MWh/year and 91.4 MWh/year, depending on the configuration and estimation technique used. These output levels are equivalent to a capacity factor in the 10.1-13.7% range. This project underscores Cornell's leadership in renewable energy innovation while demonstrating its unwavering commitment to shaping a greener future.

Motivation

As Cornell transitions to a net zero carbon emission campus, prioritizing space and resources for renewable energy becomes essential. This project embodies Cornell's transition from a campus that relied on non-renewable resources, such as coal, to a campus that strives to rely on renewable sources like solar energy. One of the main facets of Cornell's Climate Action Plan (CAP) is green development, which involves maximizing usage and productivity of on-campus buildings in terms of energy and space. As the coal pile at the Central Heating Plant on Cornell's campus retires and renewable energy goals are proposed, this project becomes an opportunity to transform under-utilized spaces into sustainable and productive spaces by installing the relocated solar PV array on this site.

Goals

The primary goal of this project is to design and develop a process to relocate the photovoltaic array from the roof of the HEB building to the place of the former coal pile by the power plant. This will require numerous steps to achieve, the first of which is an understanding of the amount of space the coal pile provides compared to the roof, and what configuration of the panels works best in the new area. We will also need to uncover the best way to provide support for the panels, either by reusing the stands from the roof or by finding if there is a cheaper or more stable alternative that being on the ground provides.

There are a few additional goals we will be working towards on the project, such as better understanding the energy generation that the solar array provides throughout both the year and the day. We can additionally find if any small improvements can be made to the array during the moving process, such as seeing if a change in the tilt angle could help increase generation. We would also like to find the cost of installation for the entire process, including the costs of new parts and equipment, removal, and placement.

Another part of the project will be an analysis of adding an energy storage system next to the array at its new location. This assessment will include its feasibility, potential storage methods, and costs.

Individual Backgrounds:

Elyse Forcier:

Elyse received a bachelor's degree in environmental science from Stockton University in the class of 2023, before pursuing a Master of Engineering in environmental engineering from Cornell University in the class of 2024. Elyse is interested in pursuing a career in sustainable transportation, ideally in the field of biomass energy production as a clean fuel source for vehicles.

Deacon Mayock:

Deacon completed his bachelor’s degree in environmental engineering at Cornell University in December of 2023, and is now working toward a Master of Engineering in environmental engineering from the same school. Deacon likes renewable energy production and is interested in a career towards feasibility studies and analysis of renewable energy projects.

Pradnya Rangari:

Pradnya completed her bachelor’s degree in mechanical engineering from Rashtrasant Tukdoji Maharaj Nagpur University in August 2021, and is now pursuing a Master of Engineering in environmental engineering from Cornell University. Pradnya is interested in hydrology, sustainable and renewable energy and its environmental impacts.

Katie Lee:

Katie is completing her bachelor’s degree in civil and environmental engineering at Cornell University and is expected to graduate in May 2024, and working towards a Master of Engineering in civil and environmental engineering at Cornell University. Katie is interested in renewable energy systems and pursuing a career in this field.

Brooke Paykin:

Brooke is completing her bachelor’s degree in environmental engineering at Cornell University and is expected to graduate in May 2024. She is also working towards a Master of Engineering degree in civil and environmental engineering at Cornell University and is expected to graduate in Dec 2024. Brooke is interested in pursuing a career in renewable energy engineering.

Scoping statements

In an effort to narrow the focus of this project to reach our specific goals, some considerations were excluded from the scope of the project.

1. The timeline of construction and installation are excluded from our proposal as we cannot control such factors.
2. The energy costs for the installation and the energy lost in the process is not being considered in this proposal.
3. The energy demand charges which are dictated by the rate of power consumption are also not included in the scope of this proposal due to the relatively low change in energy generated compared to the prior location.
4. Lastly, stormwater management systems and concerns of sediment erosion are not being included in this proposal.

The topics which are included in this report include:

1. The amount of energy expected to be generated by the solar array in the new location, paying attention to meeting the previous demand of energy production.
2. The angle of the solar panels is being included in this proposal in effort to maximize the capture of solar energy year-round.
3. The placement of the solar array is being carefully considered in this proposal for the same reason, as the arrangement can directly affect the amount of energy generated.
4. Similarly, we are considering the potential for installing additional solar panels if the dimensions of the new location allows.
5. The installation of the solar array is being considered in the sense of ensuring the array is properly installed with respect to the surface of the ground and any elevation changes or soil compaction issues which may arise.
6. The cost of installation is included in this proposal, including the materials, labor, and other expenses associated with the installation of the solar arrays.
7. Also included are the logistics of wiring and connection between the solar array and the grid.
8. Due to the location’s prior purpose as coal storage, some demolition of coal-related infrastructure may be needed, and such costs and logistics will be included in this proposal as well.
9. Lastly, we are including energy storage potential, in an effort to use renewable energy sources as much as possible on the Cornell campus, the option of storing excess energy in batteries is being considered.

Introduction

Cornell University is an institution known for striving for excellence, and in an effort to achieve excellence in sustainability, the Climate Action Plan (CAP) was created in 2009. This program is overseen by a variety of different committees and working groups who implement the strategies necessary for progress to be made on Cornell's campus. The main goals of CAP include Green Development, Energy Conservation, and Renewable Energy, all of which must seamlessly integrate the use of renewable energy sources in order to the campus. Cornell has made progress in the utilization of renewables, such as solar, hydroelectric, lake source cooling, and earth source heating, however, CAP encouraged the long-term goal for the campus to be run on 100% renewable electricity, therefore the optimization of the renewable energy currently implemented on campus is crucial. While large projects are slated to be added to the campus in the coming years, including a 110 MW solar farm to be added by 2027 which will allow the campus to be powered by 95% renewable electricity on a net year-round basis, the existing solar farms must be optimized and utilized as best as they can be (Climate Action Plan, 2009).

Energy generation from renewable sources is paramount to reaching carbon neutrality, and Cornell has emphasized this throughout their Climate Action Plan. Primary energy use from clean resources would need to account for all the cooling, heating, and other electricity use across Cornell's campus. Way back in 2000, before the creation of the Climate Action Plan, Cornell finished their lake-source cooling project to chill buildings during the warmer months. This project takes water from the depths of nearby Lake Cayuga and supplies it to both Cornell and Ithaca High School for low emission cooling. Not only does this significantly reduce the amount of greenhouse gas emissions used for cooling, but it also decreases the total energy used for cooling in general by about 85% (Lake Source Cooling).

The current plan for generating Cornell's heating without fossil fuels is to utilize geothermal heating. Cornell will drill deep into the Earth's subsurface to flow water through high temperatures. The water would then travel to buildings across campus to provide warmth via heat exchangers. The area around Ithaca is actually a region of higher subsurface temperatures compared to the rest of the eastern United States. This project would replace all of the natural gas that Cornell currently uses for heating, reducing emissions by a massive margin of about 50,000 tonnes CO2 equivalent (Climate Action Plan, 2009). Heating would also be supplemented at peak demand with biofuel resources in case fluctuations prevent the Earth source heating from meeting all of the heating requirements (Earth Source Heat). Cornell is still determining whether geothermal heating is a viable option on campus, and a decision will be made sometime soon. In case the deep well project is found to be unviable, Cornell will likely use shallow wells as a replacement.

Cornell has emphasized renewable electricity generation for a while now, having developed fifteen projects in the Ithaca area to set up solar energy, nine on campus buildings, and six solar farms nearby. On average, these projects produce over 20% of electricity demand on campus per year, but on some very sunny days they are able to meet 100% of campus needs (Solar Energy). Cornell has two more solar farms expected to be completed by 2027, with one being a whopping 110 MW, which is almost four times the rating of all six current solar farms combined. These two projects are expected to increase the solar contribution to electricity needs on campus to over 95% (100% Renewable). The big problem with using a majority of solar energy is the intermittency of it, as how sunny it is varies greatly per day and during different seasons. This means that at times, all the solar projects will not be meeting electricity needs, and other times they will generate far more than is required. Cornell has some plants that can help mitigate this, such as their hydroelectric power plant which produces 5 to 7 million kWh in a typical year and is much more dispatchable than solar; however, the university should consider developing a large amount of energy storage to make the solar output more consistent, generating storage during times of high output such as the daytime or in the summer, and dispatching the stored energy during times of low output like nighttime and the winter.

Current Location

The solar array which is the focus of this report is currently located on the roof of the Human Ecologies Building (HEB) and consists of 228 individual solar panels, standard silicon based, each with an output of 305 Watts, totaling to 76 kW of electricity generated annually. The array was installed in 2015 and has a purchase agreement of 20 years, giving the array another 11 years of potential use. Within the past 9 years since installation, the roof of the HEB has acquired concerning damages, prompting the decision to replace the roof entirely, creating an opportunity for the solar array to be relocated. The location of the rooftop comes with particular challenges, such as barriers to access, and the various roof safety procedures and precautions which must be taken to comply with OSHA (Occupational Safety and Health Administration) workplace safety regulations. Relocating the array to a more accessible place, namely on the ground, will remove these barriers, and allow easier maintenance of the solar array moving forward. Additionally, the panels are currently arranged individually, not racked, meaning they take up a significantly higher amount of surface area as they need roughly 8 feet between each panel to minimize shading of one panel onto another. They are also fixed at a 20° angle, directly south facing, as this is the standard practice for most solar array installations. These features of the array can be optimized in the projected location to maximize the potential output of the array. Doing so would be in line with the CAP goals of powering the university on renewable energy and ensuring the conservation of energy to increase the energy efficiency on campus.

Proposed Location

The location at which the solar array is proposed to be relocated to is across campus, at the Humphreys Service Building, the energy plant which supplied power to the campus. The plant used to run on coal power until recently, when the plant switched to running on natural gas, provided by New York State Electric and Gas (NYSEG). The existing infrastructure is reminiscent of the coal powered era, with a large grassy area left empty, which used to be the coal storage location. This area, referred to as the Coal Pile, has an area of roughly 27,000 ft^2, and sits completely empty. A Digital Elevation Model (DEM) was constructed to evaluate the slope of the area of interest. It was found that the land has a slight change in elevation, with a slope of 6.6-9.8 ft, with the lowest side being the northwest, and the highest end on the southeast (Figure 1). The area is confined by access roads which surround it on all sides and cannot be blocked, and there is a significant amount of area taken up by the large conveyor belt which used to transport coal into the furnace. This infrastructure cannot be removed for the sake of this solar array relocation project, however, it is a future possibility which is worth consideration for the potential increase in output of solar energy. This location was chosen because of the proximity to the energy plant on campus, allowing for efficient transmission of energy directly to the plant and thus the campus, as well as providing easy access to the array for any maintenance which might be needed. This would also be convenient in the event of a total power outage, as the energy plant requires some electricity to operate, so in the event of a black start, the solar array can provide the initial electricity needed to get the plant operating again. In this scenario, the solar array would have sufficient stored energy in a storage medium and could provide both the power and the correct alternating current oscillation to restart output from the Cornell electric generation plant. Once the plant is running again, the solar array would return to generating electricity as normal, since the Cornell power plant generates sufficient alternating current to meet campus demand.

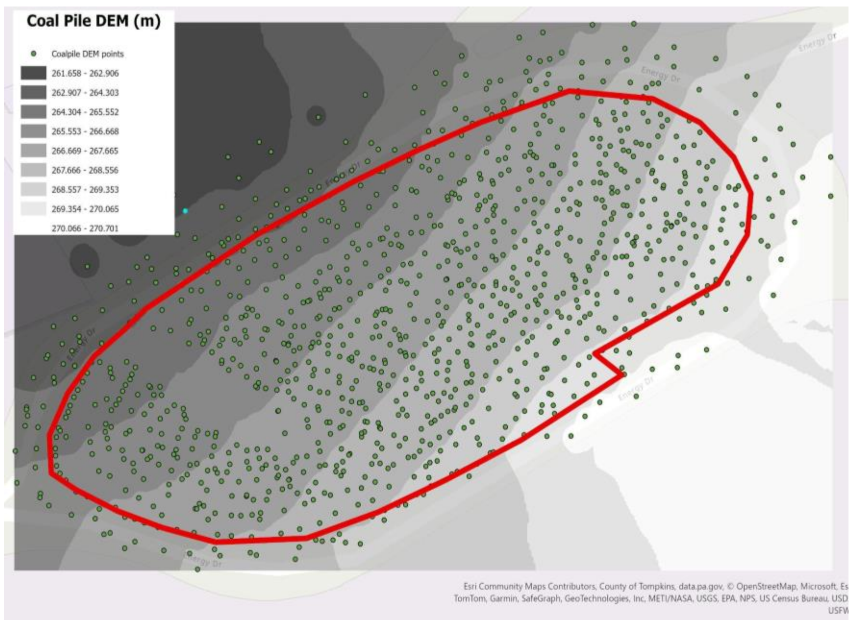


Figure 1: Digital Elevation Model (DEM) of coal pile. Each green point represents a single sample of elevation from Google Earth.

Tilt Angle Considerations

As mentioned previously, the roof-mounted system is currently at a fixed-tilt angle of 20° as a manufacturer standard and a part of our optimization evaluates this fixed-tilt angle system compared to others that may be available. The systems that are being compared as our preliminary analysis on tilt angle optimization are the fixed-tilt angle, vertical single-axis tracking, and a horizontal single-axis tracking system.

The fixed-tilt angle system refers to a constant tilt angle being held throughout the year, often used for roof-mounted systems because of their simplicity and minimized costs. Single-axis tracking refers to a system that is able to “track” the sun’s movement throughout the day or the year. A vertical-axis tracking system refers to one that has an axis fixed from east to west, therefore the panel is allowed to freely move its tilt angle facing more perpendicular north or south. This system is beneficial for areas that experience high variability throughout the months of the year due to the tilt of the earth. For example, areas of high latitudes that experience extremely different sun exposure for different seasons. These systems are often simplified into seasonal-tilt systems, meaning the tilt-angle is only altered once per season for ease of adjustment and eliminating the need for a separate motor. A horizontal-axis tracking system is more commonly used and refers to a system that has an axis fixed from north to south, therefore the panel is allowed to freely move itself facing more east or west. This system is beneficial to track the sun throughout the day, as it moves from east to west from sunrise to sunset. These horizontal-axis tracking systems can have panels that are completely parallel to the ground, known as horizontal single-axis solar trackers (HSATs), and are beneficial in areas of low latitude. They can also have a fixed tilt-angle from north to south, but still be allowed to freely face more east or west throughout the day, known as horizontal tilted single-axis solar trackers (HTSAT).

As a preliminary estimate for monthly output for different tilt-angling systems, we used the NREL photovoltaic simulator known as PVWatts. After inputting the design specifications given by the current manufacturer of the solar arrays, CSUN, monthly and hourly outputs in kWh can be obtained.

Fixed-Tilt Angle System

The general trend of varying tilt-angle in Ithaca, NY was first analyzed using the outputs from PVWatts and it was clear that there was not a constant optimal fixed-tilt angle. As seen in the figure below, during the winter months, the tilt-angle that produces the greatest output is closer to 90°; however, during summer months, we observe the opposite and that angles closer to 0° produce the greatest output (Figure X). This is due to the latitude of the region of interest being in the northern hemisphere and further away from the equator. Overall, this exercise allowed us to gauge the effects of changing tilt-angle for a system with other design specifications and losses kept constant. It also allowed us to gain a general estimate of at which tilt-angle would optimal to a 10° specificity.

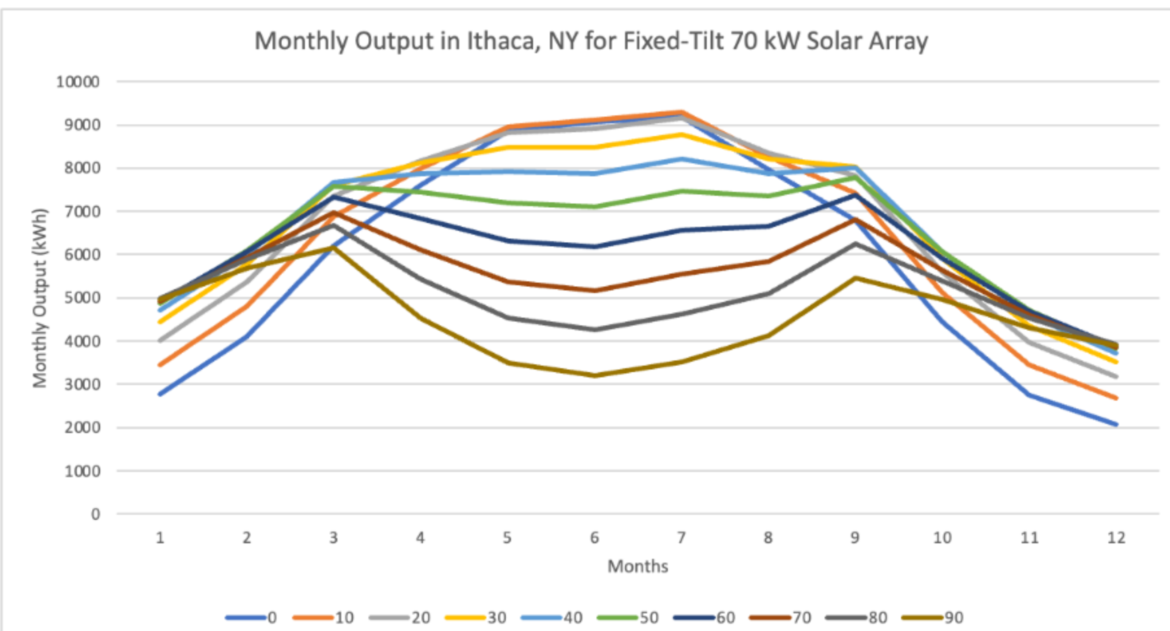


Figure 2: Monthly output for 70 kW system located in Ithaca, NY for varying fixed-tilt angle configurations

Using the results of the previous exercise, we were able to determine that the optimal value was between 20° and 30°. Again, using PVWatts and extrapolating yearly output, it was found that the optimal fixed-tilt angle value was 29.4°. At this optimal angle, the yearly output was determined to be about 81.7 MWh per year. The 20° system was also analyzed using PVWatts and it was found to output about 80.7 MWh per year, resulting in a difference of about 1 MWh per year.

Vertical Single-Axis Tracking

PVWatts does not have a vertical single-axis tracking system feature, unlike the fixed-tilt system and horizontal single-axis tracking system, therefore, to model the behavior of this type of system, it is assumed to follow the optimal fixed-tilt angle per month. For example, the optimal tilt angle in February is 50°, then it becomes 40° in March, so the vertical single-axis tracking system changes to the optimal tilt angle per month and the yearly output is equivalent to the sum of all the optimal fixed-tilt angle outputs for every month. This results in an output of 85.3 MWh per year, with a difference of about 3.7 MWh per year compared to a 29.4° fixed-tilt angle system and a difference of 4.6 MWh per year for a 20° fixed-tilt angle system. The percent difference compared to the optimal fixed-tilt angle system (29.4°) and the current fixed-tilt angle system (20°) respectively are 4% and 6%.

Horizontal Single-Axis Tracking System

PVWatts allows for a horizontal single-axis tracking system to be modeled and tilt-angle can be specifically defined, but it can also be kept at 0° to convey a panel with tracking abilities and no altered tilt-angle. Parallel or non-tilted horizontal single-axis tracking systems are often used because they have smaller costs and are simpler for installation. In this case, it would be assumed that the tracking system would involve a motorized component that would allow the angle to be changed throughout the day to match the movement of the sun. The output for this 70-kW system in Ithaca, NY with a horizontal single-axis tracking system parallel to the surface was determined to be 91.4 MWh per year. Compared to a fixed-tilt angle system at 29.4°, this produces 9.7 MWh more per year; compared to a fixed-tilt angle system at 20°, this produces 10.7 MWh more per year. The percent differences between a parallel horizontal single-axis tracking system and a fixed-tilt angle system at 29.4° and 20° respectively are 12% and 13%.

Horizontal Tilted Single-Axis Tracking System

The horizontal tilted single-axis tracking system has a distinct feature on PVWatts and was used in our analysis of the different tilting systems. It was assumed that the tilt of the system was still kept at the optimal 29.4° for this case and the other design specifications would be kept constant. The output of this size system in Ithaca, NY was determined to be about 98.9 MWh per year with a difference of about 17.3 MWh per year for the 29.4° fixed-tilt angle system and a difference of about 18.2 MWh per year for the 20° fixed tilt angle system. Resulting in a percent difference compared to the optimal fixed-tilt angle system (29.4°) and the current fixed tilt angle system (20°) respectively 21% and 23%.

Comparison of All Tilt-angle Systems

The comparison for all of three of these systems, fixed-tilt angle system, vertical single-axis tracking system, and the horizontal tilted single-axis tracking system, can be seen in the figure below (Figure X). Horizontal tilted single-axis tracking systems of this size at this location were found to have the highest monthly output throughout, and therefore the highest final yearly output. The benefits of the horizontal tracking system over the two other systems can be most seen during the summer months when sun irradiance is the greatest for the region of interest. For the vertical tracking system, we can see that the summer months again also provide the greatest improvement, but also slightly during the winter months. And as for the fixed-tilt angle at 20° and 29.4°, we can see there is a tradeoff that occurs during the winter and summer months; where the 20° fixed-tilt angle system outperforms the 29.4° system during the summer months, however, underperforms during the winter months. Ultimately, the horizontal tilted single-axis tracking system provides the greatest output in comparison to all the different tilt-angle systems and the next step is to consider the economic tradeoffs involved.

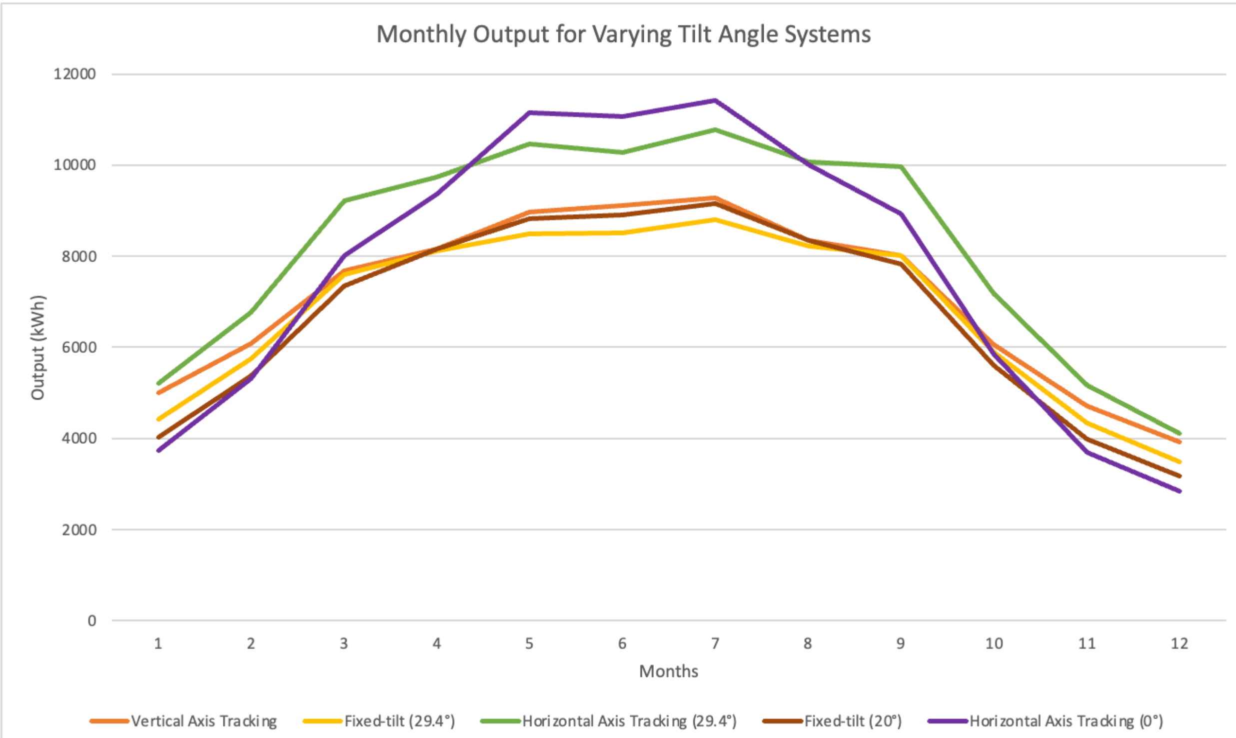


Figure 3: Monthly output for 70 kW system located in Ithaca, NY for a fixed-tilt system (29.4°), fixed- tilt system (20°), vertical-axis tracking system, and a horizontal tilted single-axis solar tracker system set at 0° and 29.4°

Racking Considerations

As mentioned previously, the array is currently arranged with panels being mounted to the roof individually. This layout is satisfactory for a rooftop location, however on the ground, the panels can be arranged in a more compact and convenient manner, known as racking. The racked mounting option consists of 4 rows of 12 panels, though some panels can go up to 14 panels per row. The panels are attached to aluminum tracks and secured in order to remain structurally sound in order to withstand high winds, heavy snowfall, and other conditions. These can either be fixed at one angle or utilize single-axis or double axis tilting, as mentioned above.

Let us first discuss the option of preserving the individual mounting layout on the Coal Pile, then we will compare this layout to a racked option. The objective of the layout should be to minimize shading of one panel onto another, and maximizing the solar radiation reaching each panel. While a minimum of

100% solar radiation would be ideal, it is safer to work with the assumption that there will be 10% shading, caused by any number of unknown variables such as tree branches, snow cover, etc. Assuming a minimum of 90% unobstructed sun exposure, the panels were calculated to need 8.8 feet of spacing between each panel to reduce shading. This calculation was made using the following equation, with *L* representing the panel length, in this case that value is 77 inches, *tilt* representing the panel tilt angle, 29.4°, and *lat* representing the geographic latitude of the location, 42.4°.

Eq. 1 $$X = L\,(\cos(tilt) + (\sin(tilt) * (\tan(lat + 23.5 + (50\%\ \text{of elevation})))))$$

One challenge with this estimation is that the equation assumes the surface on which the array is installed is level, which is not the case for the location in question. The Coal Pile contains a roughly 3 ft elevation change, which will need to be accounted for in the layout and installation of the array. While the 8.8 ft spacing is a good guideline, there will need to be adjustments made in order to truly maximize the sun exposure.

In the case of racked mounting, the same variables and assumptions were used to determine the spacing needed for each rack to maximize the sun exposure. Due to the significant height of the racks, the optimal spacing was found to be 35 feet between each rack. This shows how different locations are better suited for individual arrangements, while others with more ample surface area can accommodate this larger spacing (see Appendix for layout designs). As mentioned previously, the slope of the Coal Pile will likely require alterations in the spacing and installation of the racks so as to not cast shadows on the racks on the lower elevation areas.

Lastly, when choosing a racking system, it is essential to look toward the future and consider whether or not more solar panels will eventually be installed on the old coal pile site.. Both the layout in Figure 3 and the layout in Figure 5 contain the same number of solar panels as currently exist on the roof of the HEB building. These figures prove that the current solar array system could be installed as a racking system or as an individual system. However, the two mounting systems do not have the potential for expansion. Analyzing Figure 3 shows the racked system would not be able to fit even one additional rack onto the solar site. On the other hand, Figure 5 shows there is much empty space left over if the solar panels were installed individually. Figure 6 contains all of the same solar panels that were in figure 5 in an identical configuration, and has added in more solar panels to show the potential for expansion. More specifically, Figure 6 has 176 more solar panels in its layout than Figure 5 has. If in the future, Cornell may want to add more solar panels to this site, it is recommended that when the panels from the HEB building are placed on the coal site, they are individually mounted instead of racked as this leaves more room for expansion.

Economic Analysis

In order to investigate if the investments towards these changes to the solar array would result in savings for Cornell, an economic analysis was also conducted. Both the changes to the tilt-angle system and the racking systems were evaluated in the economic analysis.

Beginning with the economic analysis on the tilt angle systems, the two chosen systems to compare were the fixed-tilt angle system and the horizontal single-axis tracking system. This is because the fixed-tilt angle system is the control system, as it is the current system that is used and the least expensive out of all three tilt-angle systems studied. The horizontal single-axis tracking system was chosen because it produced a significantly greater output than the vertical single-axis tracking system, is more commonly used in this region of interest, and are a less complex system than a horizontal tilted single-axis tracking system. As mentioned previously, the output of the fixed-tilt angle system (assumed to be the 29.4° system) and the horizontal tilted single-axis tracking system are about 81,600 kWh per year and 91,400 kWh per year, respectively. Resulting in an output difference of about 17,300 kWh per year, and using the cost of electricity at Cornell University that is $0.0748/kWh, we can estimate that the savings incurred from using a horizontal single-axis tracking system would be about $725.24 per year from avoided electricity purchases.

Next, is determining the costs involved in these two different systems, specifically the capital and operational costs. An aggregation of sources reviewed by National Renewable Energy Laboratory were used in this analysis (NREL, 2021). For the capital costs, tracking systems will typically always be more expensive, found to be about $1.01/W, resulting in $70,700 for the total capital costs for a horizontal single-axis tracking system. This value may vary depending on whether the system is tilted or kept parallel to the surface. The capital costs for a fixed-angle system were found to be about $0.94/W, resulting in $65,800 for the system of this size, and a difference of $4,900 between these two systems in terms of capital costs. Operating and maintenance costs for the tracking systems are also found to be more expensive, about $17/kW-per year; whereas fixed-tilt angle systems are about $16/kW-per year. This results in yearly operating and maintenance costs for a tracking system and a fixed-tilt angle system to be about $1,142 per year and $1,222 per year, respectively. Yearly difference between these is found to be about $80 per year, however important to note that operational and maintenance costs will vary depending on model type, inverter types, vegetation and pest management, and other factors that may not be relevant to Cornell's system. The summary of the differences in performance and costs can be found in Table 1 below.

Combining the capital and operational costs, the yearly expenses can be calculated and compared to the yearly savings generated from the changes in the tilt-angle system. The time it would take for the return of investment was determined to be at least 7.6 years for a horizontal single-axis tracking system to be worth investment. It is also important to note that these solar modules are not newly manufactured and have a shortened lifespan, having been implemented in 2015. An average lifespan of a solar module is about 30–35 years, and assuming the lower boundary, then the remaining lifespan of these modules is about 21 years. Leaving then about 13 years for savings to be incurred, which can culminate to about $8,388 assuming that operation is consistent and operational costs do not fluctuate.

	Fixed-tilt	Horizontal single-axis Tracking	Difference
Yearly Output	81,600 kWh	91,400 kWh	**~9,800 kWh**
Capital	$65,800	$70,700	**$4,900**
Operational*	$1,142 per year	$1,222 per year	**$80 per year**

Table 1: Summary of Differences in output of Fixed-tilt and Horizontal single-axis tracking systems

Energy Output

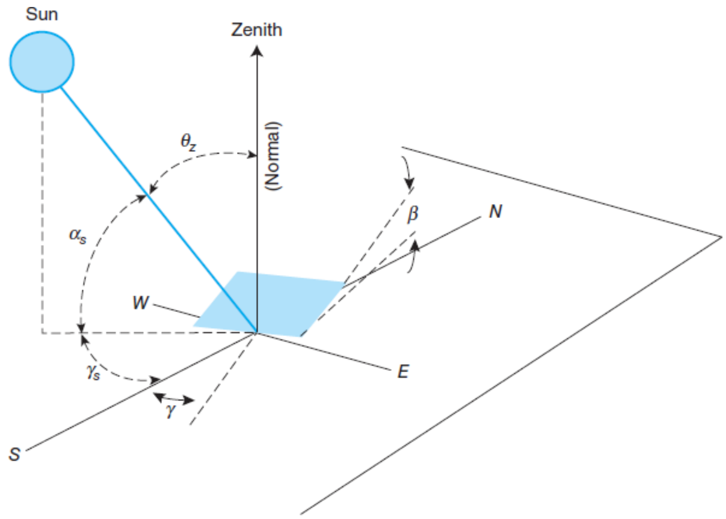
To verify the PVWatts values given for our system, as well as to better directly compare different tilt angles for daily, monthly, and yearly output. To develop a detailed model for the estimated output of our system, we turned to Matlab to run calculations for each hour of the year. Using the estimated hourly insolation, we can calculate the amount of energy received and converted to electricity by finding the various efficiencies important to solar production. The primary three types, and the ones we are focusing on to estimate output, are efficiencies from geometry, from diffusion, and from the solar cell temperature.

While the average insolation from the sun onto earth is about 1368 W/m^2, that value can only truly be achieved from a direct, straight line to the earth's surface. Since our solar panel is tilted, and the rotation and revolution of the earth causes the sun's relative position in the sky to be constantly changing, only a percentage of the direct insolation can reach our tilted panel.

The first value needed is the declination angle, or the angle between the sun and the equator. This changes based on the day of the year as seen in the equation below:

$$\delta = 23.45 \sin\left[\frac{360\,(284+N)}{365}\right]$$

The declination angle, along with the hour angle $\omega = 15°(\text{hour} - 12)$ will allow us to find the two angles needed to find the geometric efficiency, the solar altitude and the solar azimuth angle. Figure 5 shows what these two angles mean from a geometric standpoint, as well as some others that will be valuable later on.



Legend for symbols	
Greek symbol	**Definition**
α_s	Solar altitude
β	Slope angle (of device)
γ	Surface azimuth angle
γ_s	Solar azimuth angle
θ_z	Zenith angle

Figure 5: Diagram of important angles between the sun and a solar panel (Vanek)

The solar altitude can be found from the following equation using the declination angle, hour angle, and latitude:

$$\sin \alpha = \sin \delta \sin L + \cos \delta \cos L \cos \omega$$

The solar azimuth is then derived from the solar altitude, declination angle, and hour angle:

$$\sin \gamma_s = \cos \delta \sin \omega / \cos \alpha$$

The overall geometric efficiency is equivalent to the cosine of the angle of incidence:

$$\cos \theta_i = \sin \alpha \cos \beta + \cos \alpha \sin \beta \cos (\gamma - \gamma_s)$$

Where β is the tilt angle of the solar panel, and γ is the azimuth angle of the solar panel, which will always be equal to 0 as it is oriented to face directly south.

The next efficiency needed to be determined is from the losses incurred from the diffusion of sunlight within the earth's atmosphere. This can be from cloud cover preventing solar penetration to the ground, as well as general scattering of energy in the air. To find the efficiencies, we need to utilize the clearness index K_T, as well as daily insolation values, H, for Ithaca, with the final goal being to calculate H_T or the total daily insolation reaching our tilted solar panel. The following equations allow us to determine these values
Table X gives us the average monthly values of K_T and H, with H being in terms of MJ/m^2. With these values, and knowing the tilt, latitude, and declination angles, all we need to determine the daily insolation

$$\overline{H}_d/\overline{H} = 1.39 - 4.03\overline{K_T} + 5.53\overline{K}_T^2 - 3.11\overline{K}_T^3$$

$$\omega_s = \cos -^1 \left[- \tan \left(L \right) \tan \left(\delta \right) \right]$$

$$\omega'_s = \min \left\{ \omega_{s'} \cos^{-1} \left[- \tan \left(L - \beta \right) \tan \left(\delta \right) \right] \right\}$$

$$\overline{R}_{b,\beta} = \frac{\cos \left(L - \beta \right) \cos \left(\delta \right) \sin \left(\omega'_s \right) + \omega'_s \sin \left(L - \beta \right) \sin \left(\delta \right)}{\cos \left(L \right) \cos \left(\delta \right) \sin \left(\omega'_s \right) + \omega'_s \sin \left(L \right) \sin \left(\delta \right)}$$

$$\overline{R} = \left(1 - \frac{\overline{H}_d}{\overline{H}} \right) \overline{R}_{b,\beta} + \left(\frac{\overline{H}_d}{\overline{H}} \right) \left(\frac{1 + \cos \left(\beta \right)}{2} \right) + \frac{\rho \left[1 - \cos \left(\beta \right) \right]}{2}$$

$$\overline{H}_T = \overline{H}\,\overline{R}$$

relative to typical values is ρ, the ground reflectivity, which is determined by the nearby type of ground. For our new location, this will almost always be grass, with the exception of days in winter often being snow. The ground reflectivity of grass is 0.25, while that of snow is 0.70. We will assume that the reflectivity remains at 0.25 year-round to avoid having to account for sporadic snow in Ithaca, which has been especially decreasing in recent years.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\overline{K}_T$	.351	.435	.450	.428	.502	.538	.554	.530	.497	.465	.324	.337
$\overline{H}$	4.95	8.61	12.26	15.08	20.28	23.10	23.15	19.80	15.05	10.47	5.31	4.90

Table 2: Clearness index and daily insolation average monthly values (Vanek)

Finally, we can start determining the last efficiency, coming from the cell. The following equation determines cell efficiency:

$$\eta = \eta_r \left[1 - \beta \left(T_c - T_a \right) - \beta \left(T_a - T_M \right) - \beta \left(T_M - T_r \right) \right]$$

where η_r is the rated efficiency of the cell, 15.7%, β is the temperature coefficient of efficiency, 0.0041/°C, T_c is the cell temperature, T_a is the air temperature, T_M is the average monthly air temperature, and T_r is the rated temperature of the cell, 44°C. Table X gives the monthly values for each temperature difference, with the assumption that T_a - T_M will be on average 3°C for general variances.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

T_c - T_a	15.67	20.57	23.69	24.17	27.04	28.24	28.84	27.73	25.89	23.08	16.32	15.07
T_a - T_M	3	3	3	3	3	3	3	3	3	3	3	3
T_M - T_r	-46.7	-47.1	-41.8	-34.9	-28.7	-23.5	-20.7	-21.8	-26.1	-32.0	-38.7	-45.3

Table 3: Monthly temperature difference values (Vanek)

With the geometric, diffusive, and cell efficiencies all determined, we can now determine the energy that can be converted into electricity by the solar panel at any given time of year using the following formula:

$$E = A\eta_g\eta_d\eta_c I_0 \Delta t$$

where A is the area, η_g, η_d, and η_c are the three respective efficiencies, I_0 is the average direct hourly insolation, and Δt is the time range used. Given an area of 1.956 m x 0.992 m per solar panel, and 228 total panels, the following yearly values were calculated for 4 different tilt schema: fixed at 20°, fixed at 30°, seasonal tilt of 15° in the summer, 60° in the winter, and 40° in the spring and autumn, and single-axis tracking.

	20°	**30°**	**Seasonal tilt**	**Horizontal axis tracking**
Energy Output	67,530 kWh	70,761 kWh	76,725 kWh	69,410 kWh
Percent increase over 20°	0%	4.8%	13.6%	2.8%

Table 4: Estimated yearly output and comparisons for different tilt options

Interestingly, the output is highest when using the seasonal tilt values rather than single-axis tracking values. This is due to the fact that the tilt angle determined by the single-axis tracking method was based on the complement to the solar altitude, otherwise known as the zenith angle. While this does maximize geometric efficiency of the panel when the solar azimuth is 0, this can cause reductions during times other than solar noon. There are also losses in efficiency due to the diffusion calculations that make single-axis tracking not increase output a lot relative to 20°. For these reasons, using true single-axis tracking does not appear to be the most valuable method in increasing production, and rather a more complicated tracking method to maximize geometric efficiency would be a better use of funds. Comparing the results in Table 4 to results from PV-Watts, the same array with fixed 30° tilt angle and without any derating (100% efficient) generates

101,301 kWh/year, so with a derating factor of 31.5% the output from PV-Watts would be equivalent to the result of 70,761 kWh/year shown in the table.

Additional Considerations

Adding an energy storage system adjacent to the relocated photovoltaic array is a strategic enhancement that can significantly improve the overall efficiency and reliability of the solar energy system. This addition can help balance supply and demand, store excess energy generated during peak sunlight hours, and provide a reliable power supply during periods of low solar output or high demand. The feasibility of this addition involves considering space availability, integration with existing infrastructure, and alignment with the university's sustainability goals.

The current storage system at Cornell primarily involves thermal storage, with no existing electrical storage capacity. Introducing electrical storage could offer significant advantages, such as the ability to store excess solar energy generated during periods of low demand and use it during times of high demand. This has notable implications as Cornell's period of highest energy demand is during the academic semesters (late August to mid-December, and mid-January to the end of May). However, solar panels are known to generate their highest yields during the summer months as this is when daylight periods are longer and more intense. Since peak production is during the summer, but peak demand is during the academic year, storage options are considered below. Moreover, yet another reason to consider storage options is due to the potential positive impact storage options could have during a blackout. With a reliable storage option, there is the potential to initiate a black start. Thus, storage options also increase the reliability and stability of our energy supply.

1. Storage - Potential Storage Methods
   1.1. Battery Energy Storage Systems (BESS):Lithium-Ion Batteries: These are the most common type of battery storage, known for high energy density, long cycle life, and decreasing costs. They are suitable for short to medium-term storage needs and can be easily scaled based on the array's output.
   1.2. Flow Batteries: These are ideal for large-scale storage and longer-duration discharge times. They offer a longer lifespan and can handle more charge/discharge cycles without significant degradation.

Operational and Maintenance Costs: These include regular maintenance, monitoring, and eventual replacement of battery components. Lithium-ion batteries usually have lower maintenance costs but require replacements approximately every 10-15 years. Flow batteries, while having higher initial costs, can last longer with proper maintenance.

Potential Savings: By storing excess solar energy and using it during peak demand times, the university can save on energy costs and reduce reliance on grid electricity, particularly during peak pricing periods. This can also provide a buffer against power outages, enhancing campus energy security.

2. Inverter Pad Location:

Placing an inverter pad near the array can simplify the system design by minimizing the distance electricity must travel from the solar panels to the inverters, reducing energy losses and installation costs. As such, it is recommended that the inverter pad be placed on the old coal site panel.

A comparison of Figure 3 and Figure 4 show two potential locations for the inverter pad on the site layout. To decide where exactly on the site the inverter pad should be installed, it is crucial to consider shadows. There currently exists a conveyor belt(see Figure 7) in the middle of the site location, creating shadows depending on where the sun is located during the day. As such, placing solar panels next to the conveyor belt will reduce energy yield as they will not get as much sun exposure. While the area residing adjacent to the conveyor belt is unideal for the physical panels themselves, it poses no complications toward the inverter pad's function. As such, it is recommended that the inverter pad be placed close to the conveyor belt, in an area that may naturally receive shadows. This ensures that the inverter pad is not utilizing areas that are more suitable for solar panels. Figure 3 in the appendix features a site design where the inverter pad is located further from the conveyor belt, and in turn, solar panels are installed next to the conveyor belt, in an area that will be partially shadowed during certain times of the day. Figure 4, on the other hand, places the inverter pad next to the conveyor belt, leaving the unobstructed regions open for solar panel installment.

Operational and Maintenance Costs: Maintenance costs for inverters include periodic inspections and replacements, usually every 10-15 years. Properly located inverter pads can reduce operational inefficiencies and energy losses, potentially lowering long-term maintenance costs.

Potential Savings: Locating the inverter pad near the arrays can reduce installation complexity and costs, improve energy conversion efficiency, and enhance the overall performance of the solar power system.

Integrating an energy storage system alongside the photovoltaic array at its new location is a feasible and strategic enhancement. Battery energy storage systems, particularly lithium-ion or flow batteries, offer significant benefits in terms of energy reliability and cost savings, despite the initial investment. Similarly, strategically placing the inverter pad near the arrays can streamline installation and operational efficiency, contributing to long-term savings and performance improvements. This comprehensive approach aligns with Cornell's commitment to sustainability and its goal of achieving carbon neutrality, further solidifying the university's leadership in renewable energy innovation.

Conclusion

In conclusion, the project to relocate the photovoltaic array from the HEB building's roof to the former coal pile site near the Central Heating Plant is a critical step in advancing Cornell University's Climate Action Plan (CAP). Through strategic planning and analysis, we aim to optimize space utilization, enhance energy generation, and integrate advanced renewable energy technologies.

A detailed comparison of tilt angle systems—fixed-tilt, vertical single-axis tracking, and horizontal tilted single-axis tracking—demonstrated that the horizontal tilted single-axis tracking system provides the highest energy output, particularly during peak solar months. Additionally, integrating a Battery Energy Storage System (BESS) offers a practical solution to balance supply and demand, store excess energy, and enhance energy reliability, despite higher initial costs.

Strategically placing an inverter pad near the array minimizes energy losses, reduces installation complexities, and enhances overall system efficiency. In light of these findings, we recommend adopting the horizontal tilted single-axis tracking system, implementing a battery energy storage system, and strategically placing inverter pads near the arrays. These actions will further Cornell's leadership in renewable energy innovation and advance its Climate Action Plan.

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Appendix

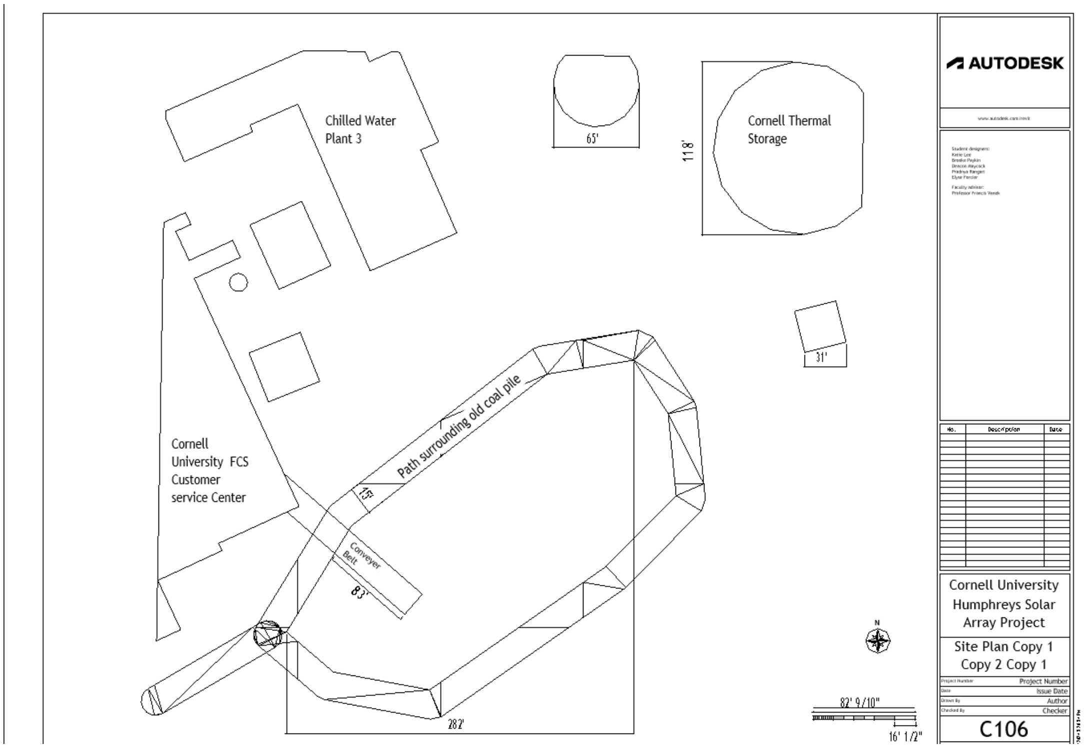

Figure 1: Revit drawing of site location

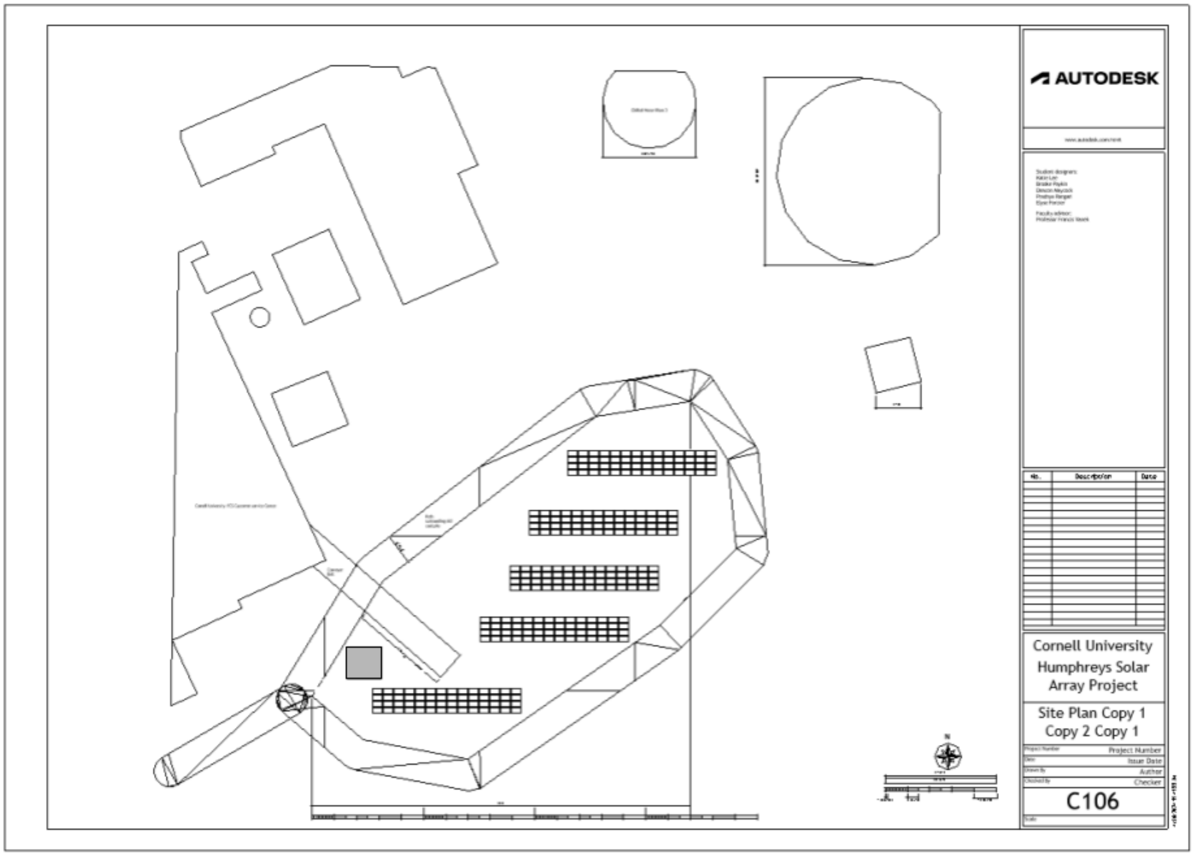

Figure 2: Revit of Proposed Solar Array Layout: Rack-Mounted

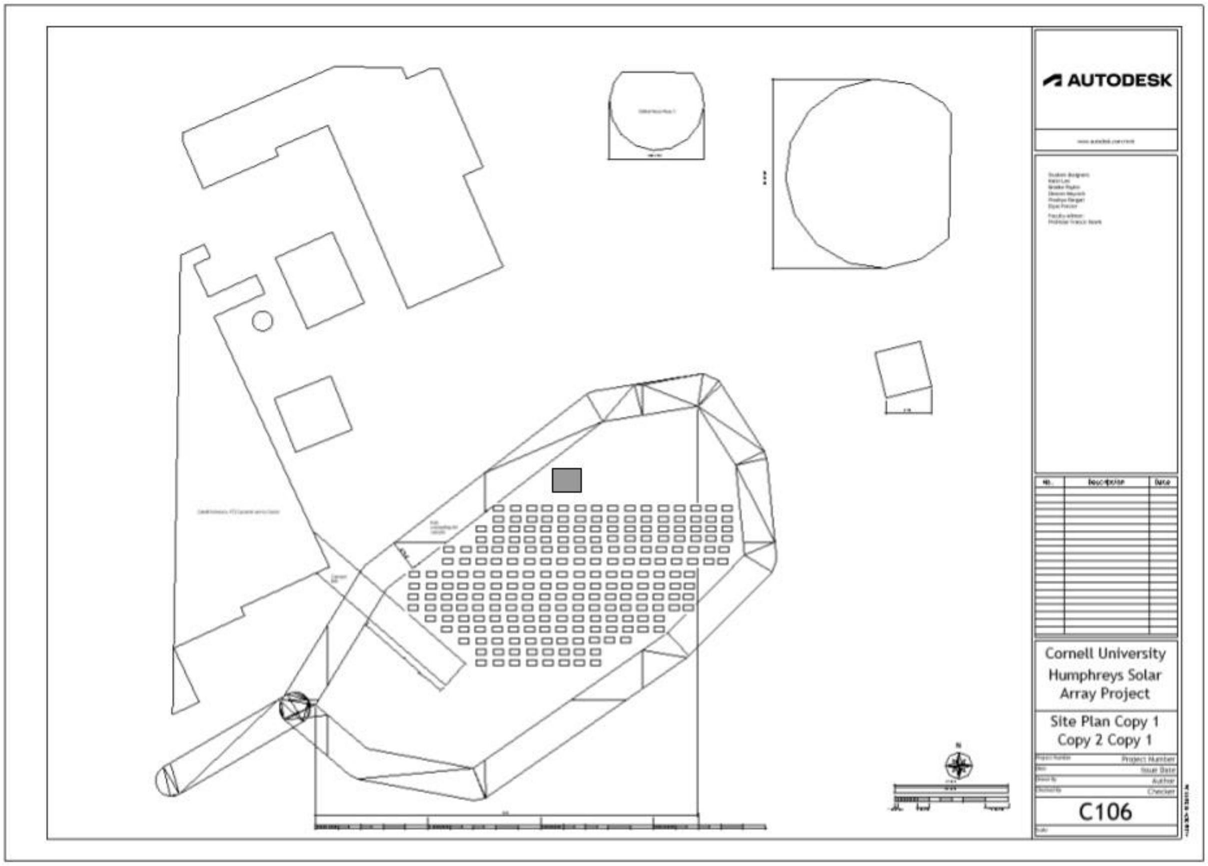

Figure 3: Revit of Proposed Solar Array Layout: Single-Mounted– panels close to Conveyer belt

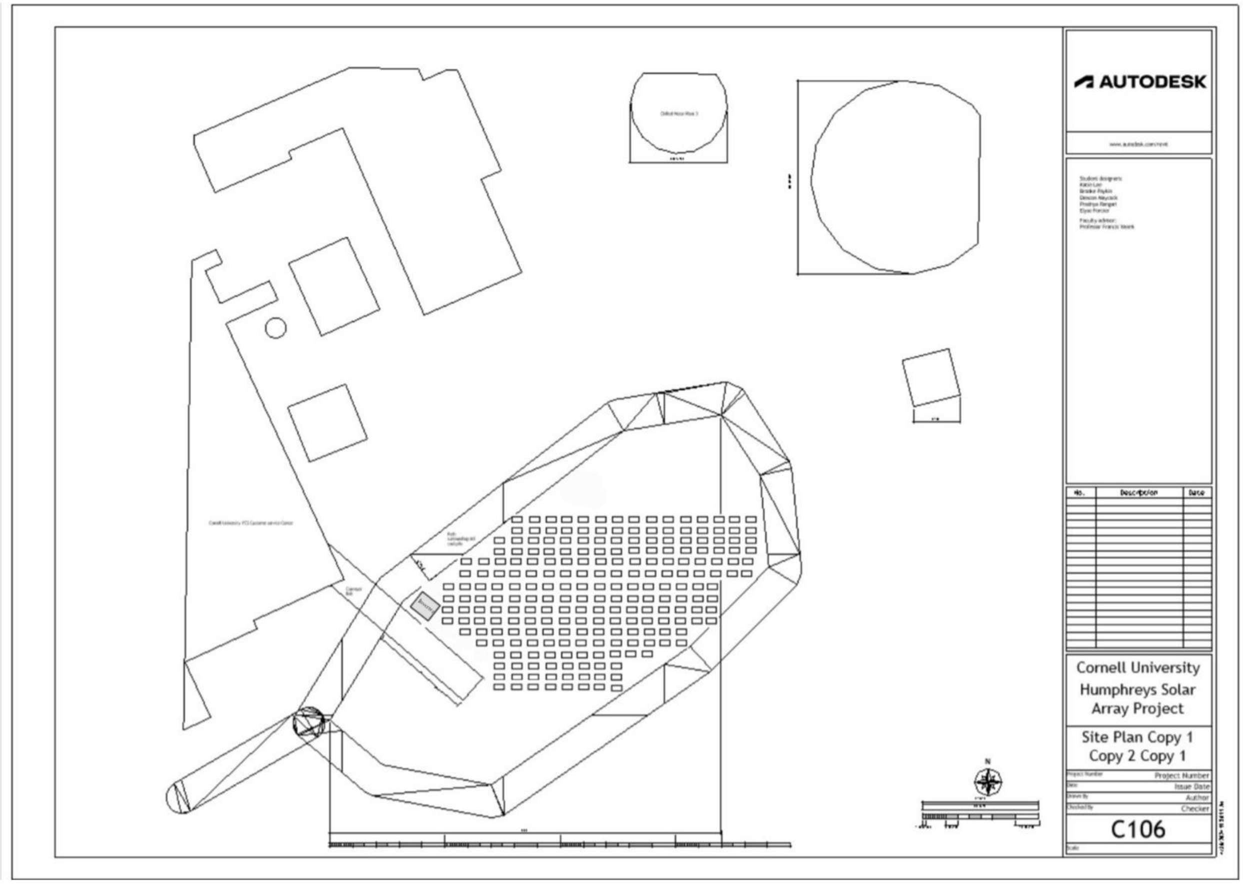

Figure 4: Revit of Proposed Solar Array Layout: Single-Mounted– panels spaced away from Conveyer belt

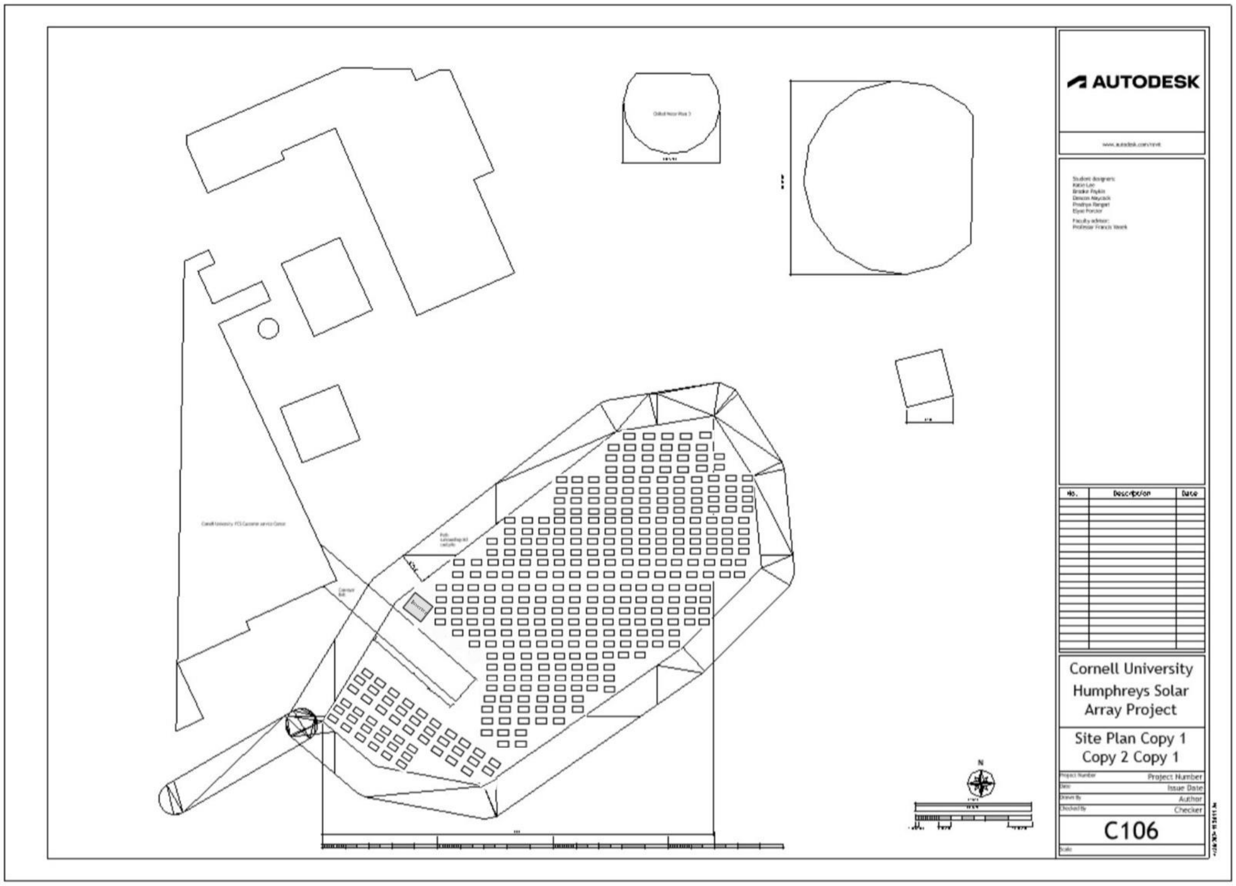

Figure 5: Revit of Potential Expansion plan of Solar Array Layout

Figure 6: Old Coal Conveyor Belt