Emissions Free Transportation for Swarthmore College

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Abstract

Transportation and electricity sectors account for over 67% of Swarthmore College’s greenhouse gas emissions in 2013. As the College explores ways to reduce its carbon footprint, this project examines how photovoltaics and electric vehicles can enable emission free transportation. In particular, we design and construct a 1.5kW ground-mounted solar array and two Level 2 AC charging stations at the Fieldhouse West parking lot. We also design a scalable solar carport structure for future implementation. Modeling suggests that this system will generate 2.2 MWh per year, offsetting the energy needed to charge 3 Swarthmore commuters. Over its design life, this system will generate 52.2MWh of solar energy and avoid 78.2 metric tons of CO2.
About the Authors

Acknowledgments

This project would not have been possible without the help of several people in the Swarthmore community. Professors Carr Everbach and Faruq Siddiqui provided excellent guidance, teaching and mentoring as advisers to this project. Laura Cacho and Ralph Thayer helped kickoff and fund the project through the Sustainability Committee’s Green Initiatives Fund. Jeff Jabco assisted the preparation of the solar array site. Bill Maguire, Tom Cochrane, Ken McNeal, and John Parks were invaluable in the construction and implementation process – these aspects of the project would not have been possible without their time and effort. James Johnson helped us obtain and prepare project materials. Michael Matotek of Open Sky Energy also provided valuable advice and expertise on solar design and installation.
1 Introduction

This senior design project involves the design and construction of a pilot solar-powered electric vehicle charging station. A secondary goal of the project was to design a full solar carport structure that could be implemented at scale. The project design and construction took place over the course of several months during the spring semester. In order to justify and properly quantify the cost of the project, an economic analysis was performed along with an examination of the avoided greenhouse gas emissions over the design life of the solar panels and the electric vehicle charging station. The ground-mounted solar array and the vehicle charger are both very visible to increase exposure to visitors to campus and to encourage students, faculty, and staff at Swarthmore College to think more about sustainability in their own lives.

1.1 Motivation

Climate change is one of the greatest threats the world faces today. Long-term climate modeling conducted by Intergovernmental Panel on Climate Change [24] warns that urgent action is needed to limit global warming to less than 2 degrees Centigrade – the limit where various physical feedbacks (in the Arctic, oceans, rainforests and tundra) could greatly accelerate warming and cause irreversible climate disruption. Climate modelers [31] found that all technological scenarios that achieve the necessary level of greenhouse gas reductions – 80% by 2050 from 1990 levels – rely on three key changes to the status quo: highly efficient energy use, major decarbonization of electricity and other fuels, and fuel switching to electricity and other low carbon supplies. These scenarios indicate that staying within the 2 degree limit is possible, but to get there countries need to aggressively pursue low carbon solutions, as soon as they can. This transition will require widespread participation from states, cities, universities, and communities alike.

At a turning point for climate action, Swarthmore College has a unique opportunity to lead the country in the transition to a low carbon economy and lifestyle. In 2011, President Rebecca Chopp announced two emission targets for Swarthmore College: 50 percent reduction in net emissions from 2011 levels by 2015, and full carbon neutrality by 2035. In 2013, the College offset 46% of its carbon emissions through wind renewable energy credits, with the commitment of 100% offsets in the future. While this effectively achieves carbon neutrality, one would think that Swarthmore ought to do more than pay their way out of their carbon footprint. Beyond these targets, the Swarthmore community should actively look for opportunities for deeper...
decarbonization and greater sustainability in college operations and individual behavior.

For this project, we focus on two areas of change: generating clean electricity, and fuel switching to this clean electricity, specifically in transportation. As shown in Figure 1, indirect emissions due to purchased electricity and due to travel combined for 67% of 2013 carbon emissions. This does not include direct emissions from campus vehicles, such as golf carts and service vehicles, which can also be electrified.

![Pie chart showing 2013 Swarthmore College GHG Emissions (MT CO2e)](chart.png)

As Swarthmore begins to evaluate ways to achieve greater sustainability, we hope this project serves as a first step towards investing in big infrastructure changes and visible new projects that promote sustainable lifestyle changes, enable people in the community to adopt clean technologies, and directly reduce the carbon generated from our campus. Moreover, such investments might be necessary to ultimately achieve carbon neutrality, as Sustainability Director Laura Cacho admits that the College may be reaching a plateau in what it can achieve without major infrastructure changes.

Well-designed, clean energy infrastructure has the added benefit of serving as a constant reminder to our community and our visitors about the gravity of climate change, our commitment to reduce carbon emissions, and inspire personal reflection on what can be done individually and collectively to ensure that the world we live in today survives two, three, four generations from now. By building up our clean
energy infrastructure today, Swarthmore can help lead the large-scale transformation needed to decarbonize our lifestyles.

1.2 Background

This project involves the design and assembly of a system that would simultaneously charge electric vehicles (EVs), such as electric golf carts, battery electric vehicles, and plug-in hybrid electric vehicles, and generate solar power for the local grid using photovoltaic panels. Nationally, transportation accounted for ~34% of U.S. energy-related GHG emissions in 2013, and is the biggest driver of indirect emissions at Swarthmore excluding purchased electricity. Though reducing vehicle miles travelled is important, reducing the carbon intensity of transportation can enable greater reductions if EVs are widely adopted. Currently, EV adoption around the country is limited by the lack of support infrastructure and consumer uncertainty regarding range uncertainty. Policymakers in California have identified infrastructure as one of the major roadblocks to broad acceptance of EVs beyond the early adopters. The California Air Resources Board and state EPA branch are currently evaluating public investments in infrastructure to help achieve the state mandate of 1.5 million ZEVs by 2025.

This project would directly enable vehicle electrification in our community, offset the Colleges electric supply costs and peak demand charges by generating zero-emission electricity, create a visible and lasting reminder of carbon-awareness and energy efficiency, and become a learning and teaching tool for engineers and environmental scientists interested in renewable energy and electrical/civil engineering. Furthermore, this project would help Swarthmore lead the greater adoption of zero-emission electric vehicles in this region and provide an example for other institutions considering implementing similar systems.

We hope that our project will encourage the College to take a hard look at investing in the energy infrastructure as a way to achieve our emissions goals for 2035 and even deeper decarbonization down the road.

1.3 Existing Systems

Integrated “solar carports” have been popular at campuses and corporate offices in California, and have more recently begun to appear in Tennessee, Florida, New Jersey, and elsewhere around the country. Often, these structures resemble a car canopy structure (such as those found in gas stations) covered in solar panels. These systems
are typically grid-tied, and sometimes will offer electric vehicle charging service in addition to its primary function of shaded parking.

There are several practical benefits to building solar panels over outdoor parking lots: (i) solar energy that is otherwise lost as heat transfer to blacktop and vehicles, which requires additional energy to cool down, can be captured and fed into the grid, (ii) compared to rooftop solutions, carports avoid roof penetration and heating effects on buildings, and (iii) compared to ground mounted solutions, carports do not add impermeable surfaces that may alter storm water drainage and cause heat islanding effects. In addition, a physical system that combines solar panels and electric vehicles promotes zero-emission transportation and generation, which can in turn encourage self-reflection in energy use.

The major downside to solar carports are the costs. Though solar panels have become much more affordable in the past five years, the construction materials for the structure (typically steel and aluminum) are still quite costly. The engineering, procurement, and construction (EPC) costs are also very high for carports because unique solar orientation and site specifications (such as geotechnical features) make most carports customized, one-off jobs. Market research indicates that most carports were installed in states with healthy financial incentives, such as Arizona, New Jersey, Massachusetts, and California, and over 80% of carports installed in 2014 occurred at government and educational institutions.

### 1.3.1 Rutgers University

In 2013, Solaire Generation finished building a massive parking lot system of solar carports at Rutgers University. The project as a whole cost $40.8 million with a capacity of 8 MW [15]. The parking lot is 28 acres and the canopies cover 4000 parking spaces. The whole system has 31,032 panels. The system as a whole. Rutgers University facilities decided not to include any storage in the project as it did not make sense for their application. On the campus, they have four electric vehicle charges. According to Professor Dunbar Birnie at Rutgers, the project was implemented by the facilities primarily for the economic payback over time. With New Jersey’s financial incentives for installing solar panels, it was a good financial investment to make the system. While there are only four electric vehicle charging stations, Professor Birnie said that a community has formed around these charging stations, and it has been possible to spread use across several different vehicles every day through communication between users. Figure 2 shows an overview of the canopy.
1.3.2 University of Central Florida

Compared with the Rutgers University installation, UCF's is relatively small. Wharton-Smith completed the project in 2010, and it cost $380 thousand dollars. The system has a 10 kW capacity with on-site battery storage. The carport structure covers 4 parking spaces and has two level 2 electric vehicle charges along with several 120V outlets. The system has 48 solar panels. Figure 3 shows a front view of the solar carport.
1.4 Objectives

Throughout the course of this project, the two central objectives were:

1. To design, build, and test a pilot solar-powered, electric vehicle charging station for Swarthmore College.

2. To design a solar carport structure that can be implemented at scale.

From the beginning, we wanted to create a system that would simultaneously be a message for sustainability and enable vehicle electrification at Swarthmore College. The research question we had for the start was: *over the course of a year, can we generate enough solar to offset the energy used to charge EVs?* If we could, this would truly achieve low- or zero-carbon transportation. We wanted to probe at this question through modeling solar output and estimating EV demand. At the same time, we wanted to install a physical system by the end of the Spring semester that would provide real benefits in terms of energy, carbon, and electric vehicle service equipment for people on campus. At the time of the report, we were aware of two faculty plug in vehicles that would have utilized a charging station.

1.5 Realistic Design Constraints

From researching existing solar carports, it became evident that economies of scale are a critical aspect of any carport project. Though we had hoped to overcome this by working with Swarthmore Facilities and engineering alumni, we soon realized that the economics of a small carport project are suffocated by the sheer amount of site work, zoning regulations, and other unanticipated costs.

Reaching out to several contractors yielded only one estimate, as the scale of the project was too small for most engineering firms to even consider it. Structural Solar LLC responded to the request for a bid, however their estimate for only the structure was $15,000 which. Including the cost of the solar panels, this would have almost doubled the $10,000 grant from the Sustainability Committee. Of their estimate, a full $9,000 were for engineering design costs which exemplifies the economies of scale for a carport project.

Furthermore, the original site for the carport was next to a diesel pump which caused some concern about the construction and would have added additional cost. However, the gas line that ran underneath the initial location took precedent and the project needed to be moved to a new location. Due to zoning issues with the
Swarthmore Borough, it was undesirable to put a full structure in the Fieldhouse West parking lot.

In addition to site and budget concerns, liability issues were also a problem. Any in-house structural design would need an external Practicing Engineer (PE) to approve it which would have added both cost and time to the project. Similar issues arose with the electrical systems, as a certified electrician has to oversee all of the electrical work. Regardless of the type of solar project however, a registered electrician would have to be involved. Fortunately, there are several electricians in Swarthmore Facilities, which meant the biggest issue was taking up too much of their time and resources.

The time restrictions also played a key part in shaping the project. Any structure and charging station would have to be installed in one semester. In addition to that, weather would also play a key factor since it would be impossible to work on anything until the ground thawed and the snow relented. Since this was the case, the scale of the project had to be manageable to construct within only a few weeks. For this reason, a ground mounted solar system was desirable.

The ground mount structure was chosen to ensure that all of the materials would be recyclable to help reduce the environmental impact of the project once the design life was reached. This tied in well with the environmental impact considerations. Without any foundations or pile-driven elements, the project could be moved in the future if any construction will take place on the land. Furthermore, almost every component in the solar structure can be repurposed as either a concrete ballast for other applications, or aluminum for the shop.

1.6 Project Materials

The main materials we used for this project were SolarWorld SW 280 Mono photovoltaic modules [30], Enphase M250 microinverters [11], Schletter PVMini ground mount kit [28], and Clipper Creek HCS-40 high power electric vehicle chargers [7]. These may be referred by their product names later in this report.

2 Theory

The purpose of this section is to provide a theoretical background on the various components in a solar carport system. A detailed explanation of solar photovoltaic (PV), power systems, and structural theory is outside the scope of this project; instead, this
section is meant to introduce parameters that will be discussed in the design of the installed system.

2.1 Basics of Photovoltaic (PV) Systems

Thanks to economies of scale, learning curve effects, and offshoring, the cost of a silicon PV cell has decreased exponentially, from $76.67/W in 1977 to $0.36/W in 2014 [10]. Declining costs, solar subsidies, and increasing efficiencies have driven exponential growth in worldwide installed PV capacity, from 40K MW in 2010 to 180K MW in 2014. Over 30 countries, including the United States, have already achieved solar PV grid parity – where the levelized cost of energy (LCOE) of an alternative energy is less than or equal to the price of conventional energy purchased from the electricity grid [27].

Solar PV systems can be loosely categorized into two types: grid-tied and off-grid. Though off-grid systems are fascinating to design, they are not expected to have a large impact on electric demand and thus are not critical to reducing the carbon emissions from the electricity sector. This project will focus on grid-tied solar PV systems.

2.1.1 Solar Radiation

Understanding the characteristics of solar radiation is critical to designing any solar energy system. Just like how power is the instantaneous amount of energy, solar irradiance is the instantaneous amount of solar radiation energy available, measured in units of watts per square meter (W/m²). Plotted over the course of a day, solar irradiance increases in a concave-down parabola, peaking at noon (also known as peak sun) at around 1000 W/m². This is due to the additional air mass that the radiation must travel through to reach the measurement device. Of the solar spectrum, silicon PV devices only respond to the visible and near infrared sections. The remainder of the spectrum is reflected or dissipated as heat, placing physical limits on PV efficiency.

From any location on Earth, the sun’s position in the sky depends on the latitude, time of day, and time of year. This is important to consider when siting PV arrays to minimize shading. The range of sun paths (also known as the solar window, shown in Figure 4) is constrained by its path on the summer and winter solstice. In the summer, the sun path is at its highest point in the sky, and in the winter, the sun path is at its lowest. At the equinoxes, the sun path is closest to the latitude of the location.
When locating a grid-tied PV array, it is best to avoid shading in any of the solar window; if that’s not possible, then it is better to prioritize the hours near noon – the peak sun hours. Even partial shading of a module greatly reduce output because individual cells are series-connected current sources [25].

2.1.2 The Ideal PV Cell and Photovoltaic Effect

The fundamental unit of a solar PV system is a PV cell – a semiconductor device, typically silicon, that converts solar radiation into a direct current. To generate a useful amount of power, cells are connected together in a solar panel; 60-cell modules are the industry standard for residential applications, but slightly larger commercial panels can have 72-cells. Panels are then strung together, like batteries, in series or parallel to form a solar array. Unlike batteries, PV cells behave like current sources and will always produce a current under solar radiation.

The semiconductor solar cell was invented in 1954 by researchers at Bell Laboratories, who were primarily interested in developing a power source for telephone systems in humid, remote conditions (where dry cell batteries degraded too quickly) [29]. Though their cells were only about 6% efficient in converting solar radiation into electric energy, they were still a huge improvement over any previous solar cells, which were around 1% efficient. For comparison, mass-market panels today typically achieve around 15%, and the most-efficient commercial panels can operate at 21.5%. These efficiency statistics are defined as the total electrical output (W) divided by the solar...
irradiance \((W/m^2)\) times the area of the panel \((m^2)\), but as we will soon explain, these often underestimate how efficient modern solar panels are relative to physical limitations.

Ideal PV cells are semiconductor wafers covered by a grid of conductive metal connections. The wafer itself consists of two layers, the p-type layer and n-type layer, and a p-n junction. The p-type layer has electron holes while the n-type layer has free electrons. The n-type layer rests on top half of the cell and is exposed to radiation. This construction is shown in Figure 5.

![Diagram 1. The photovoltaic effect](image)

Figure 5: Diagram of the PV Effect [22]

The physical process by which a PV cell generates electricity under sunlight is known as the photovoltaic effect. This effect consists of two parts: creating light-generated current (the short-circuit current, \(I_{sc}\)), and generating a potential difference across the p-n junction (the open-circuit voltage, \(V_{oc}\)). To generate a current, the photon must have energy in excess of the band-gap and create an electron-hole pair. The high energy electron is then released across the terminal, creating a current. An electric field produced by the p-n junction prevents the electron and hole from immediately recombining. As electrons are repelled from the p-type layer, and holes are repelled from the n-type layer, a potential difference is created across the p-n junction. Free electrons in the n-type layer are now able to flow through the top terminal and through loads, do electrical work, and recombine with holes at the bottom terminal. This process of photons separating electrons and holes, completing the circuit and doing work before recombining occurs continuously when a PV cell is exposed to light. Thus, there is no way to switch off a PV device under sunlight.

The aforementioned band-gap energy determines the spectral limit of a semiconductor solar panel, which casts physical limitations on achievable PV efficiency. Firstly, all photons below the band-gap energy cutoff (1.12 eV in silicon) are not absorbed by the semiconductor. Secondly, the absorbed photons only need the band-
gap energy to create an electron-hole pair – any extra energy is wasted, dissipating as heat. These two basic effects reduce the solar radiation that is available for PV energy production to around 44%. Accounting for these physical limitations helps re-frame current PV efficiencies (~15%) as impressive, if not astounding. Comparatively, corn fields, which can used for biofuels, capture solar energy at 1.5% efficiency. Even algae biofuels, which rely on photosynthesis, face a theoretical efficiency limit of 5-7%.

A typical residential solar module consists of 60 PV cells, aggregated in an internal circuit. Because each cell behaves like a current source, connecting cells in series limits the total current on the circuit to the cell with the lowest current. This can cause problems when part of the module is shaded. Newer modules may have built-in bypass diodes, which are used to pass current around groups of shaded cells or other high-resistance conditions. These can also be installed across modules in larger systems, allowing functional cells or modules on a string to continue delivering power at a lower voltage.

The current-voltage (I-V) characteristic represents the electrical output profile of a PV device. Often shown as an I-V curve, this represents all possible operating points for a given PV device at some input solar radiation and ambient temperature. Since the product of voltage and current is power, this curve also represents the range of power output. A hypothetical I-V curve is shown below, with certain characteristic points marked on it; the set of I-V curves for our solar modules is included here as well.

![Figure 6: Hypothetical I-V Curve](image)

![Figure 7: SW280 I-V Curves](image)

As shown in Figure 6, the intercepts of the curve correspond to the open-circuit voltage and the short-circuit current. From elementary circuit principles, this is intuitive because the maximum voltage for a current source occurs when it is open-circuited (zero load resistance), and the maximum current occurs when it is short-
circuited (infinite load resistance). The maximum power point is located on the knee of the I-V curve. It is the most efficient operating point for a PV device under given solar radiation and temperature. Its coordinates on an I-V curve are known as the maximum power voltage ($V_{mp}$) and maximum power point current ($I_{mp}$). From another perspective, the maximum power point can be thought of as the rectangular coordinates that correspond to the largest area beneath the I-V curve. The operating point on the I-V curve is determined by the load on the panel. Since the maximum power point is constantly changing due to changing solar radiation and temperature, inverters often come with maximum power point tracking (MPPT) to dynamically change the load to maximize PV output. Though there are several MPPT algorithms, the most common is a “perturb and observe” feedback system due to its ease of implementation: incrementally increase or decrease the operating voltage until power output no longer increases. Thus, the power output value oscillates around a maximum power value until it stabilizes [18].

Figure 7 shows a family of I-V curves at several input radiations. As shown, changes in solar radiation have a small effect on voltage, but a proportional effect on current and power output. This makes sense from the theory on the photovoltaic effect, since more light means more light-generated current. Although not shown, cell temperature also has significant effects on performance. Generally, increasing cell temperature will decrease voltage proportionally, will slightly increase current, and will output slightly less power overall. This also can be explained with physics, but is not included in this report.

2.1.3 Pairing PV with Battery Storage

Increasingly, many residential PV installers are also offering battery-connected systems. For off-grid solar system, battery backup is crucial to overcome the intermittency of solar radiation. Use cases for storage on grid-tied PV systems are not as obvious, but include load shifting under real-time electricity tariffs, participating in ancillary services, and local backup for emergencies. Traditionally, lead-acid batteries have been used for this purpose, though lithium-ion batteries may become cost-effective in the future, thanks to investments in electric vehicle battery technology. A typical PV system with battery storage would include a charge controller and a battery bank between the PV array and the inverter. For this project, battery storage was not explored in detail due to budget constraints.
2.1.4 DC-AC Power Inversion

Because PV cells output direct current, accurate DC-AC inversion is needed to supply power at electrical grid requirements (120/240 V, 60 Hz). Modern solar inverters perform two functions: DC-DC MPPT, and DC-AC inversion. The effects of these two functions is visualized in Figure 8.

![Figure 8: How an inverter converts from DC to AC (Power vs. time)](image)

Due to changing input radiation and temperature, a PV module typically has variable DC output, as shown in the gray output. By dynamically optimizing the load on the module, the inverter maximizes the PV output and obtains a linear DC output (red). The final step of converting DC to AC can be achieved through several methods. The most accurate method is to use pulse-width modulation (PWM), the same technique used for DC-AC conversion in computer electronics and embedded systems. This results in the sinusoidal AC output, shown in green. For grid-tied inverters, AC voltage must be maintained at -10% to +5% of nominal system voltage, and AC output frequency must be maintained between 59.3 and 60.5 Hz.

There are two broad categories of solar inverters: string (also known as central) inverters and microinverters. String inverters aggregate DC current from several PV modules in series and parallel before converting to AC for the grid. Microinverters work largely the same way, but invert the output of each individual module, and then aggregate AC current before feeding into the grid. Microinverters are vastly easier to install, enable modular design, and are much more scalable, but are more expensive than conventional string inverters. An additional benefit of microinverters is that they provide MPPT for each module, which can greatly improve the production of a partially-shaded array. According to a 2012 study by NREL, microinverters were found to increase production by 3.7-12.3% under various shading scenarios, relative to the reference string inverter case [8]. This suggests that even though microinverters are more expensive up front, their performance in shading environments may recoup
some or all of the additional cost over system lifetime.

2.1.5 Array Design

In addition to choosing modules and inverters, array orientation is important to consider when designing a PV system. In particular, design should maximize direct radiation to the panel over the year, subject to site constraints. This is achieved to specifying an array tilt angle, array azimuth angle, and if multiple arrays exist, array rank spacing. These orientation parameters are shown in Figure 9.

Figure 9: PV Module Orientations [9]

The tilt angle is the vertical angle between horizontal and the array surface. PV modules perform best when their surface tilt is normal to the direct beam radiation. To maximize annual PV output under ideal conditions, the tilt angle should be installed at the local latitude. In practice, seasonal sun path changes and local conditions can alter the optimal angle from the latitude. For example, longer days and sun hours in the summer may favor a shallower tilt angle for maximal annual energy. Furthermore, certain shading conditions can make it optimal to target maximum output at months with less shading. PV output is to be used for off-grid applications, then the tilt angle can be used to maximize system production for months of greatest energy demand. Solar installers typically add 15 degrees to latitude to maximize winter output, and subtract 15 degrees from latitude to maximize summer output [9].

The azimuth angle is the horizontal angle between a reference direction (typically due north or south) and the direction the array surface faces. As expected, the optimal azimuth angle is due south in the Northern Hemisphere (and vice versa). However,
PV installations on existing structures may be constrained by roof orientation and pitch. Moving the azimuth angle away from due south reduces output, and its effect is amplified at larger tilt angles. This makes optimal orientation critical at higher latitudes, such as Swarthmore, PA (39.9 degrees).

Array rank spacing is necessary to make sure that arrays do not self-shade. For this project, we did not need to consider multiple arrays for our small PV system. We also did not explore sun tracking technology because it was outside of project scope; however, this could be a future improvement on our system as tracking systems can increase annual output by as much as 40% [9].

2.2 Grid Interconnection

Interconnection is the process of connecting and operating PV and other electric systems with the local electric grid. Distributed generation (DG) is the idea of using smaller generation systems to service local loads; in contrast, traditional generation involves large generation systems (coal, natural gas, utility-scale PV) need large transmission networks to service loads on the distribution side of the electric grid. DG can reduce congestion and line losses, enable greater renewable integration, and help stabilize the grid at times of critical need. Technically, any generation system that ties in at the distribution end is considered DG. However, residential PV is one of the fastest growing DG systems in the United States, thanks to federal incentives and falling module costs.

There are two types of grid connections for PV systems: load-side (also known as load-embedded and “behind-the-meter”), and supply-side (directly connected and “in-front-of-the-meter”). Load-side interconnections use back-fed circuit breakers connected in existing service panels, so they are limited by the size of the panel’s busbar or conductor rating. The National Electrical Code (NEC) states that the sum of breakers supplying power to a busbar or conductor must not exceed 120% of the busbar or conductor’s rating. For example, a standard household 200 A main breaker and a 200 A rated busbar could have up to 40 A of inverter output-circuit OCPDs installed. The NEC Section 705.12(D) specifies additional criteria that load-side interconnections must meet.

For systems that are too large to be connected load-side, an additional service connection must be added in parallel with the existing service disconnect. This is known as a supply-side connection, and would need to conform to all the requirements of a new supply service in Article 230 of the NEC.

For our project, we are interested in tying into the local college grid using a load-
side connection, since our array will never generate more than 7 A of current (1680 W nameplate / 240 V).

2.3 Electric Vehicle Charging Technology

The SAE J1772 standard was established by the Society of Automotive Engineers as the global standard for electric vehicle service equipment (EVSE) in 2009, and is now found in every plug-in electric and hybrid vehicle. The SAE J1772 is compatible with four different charging levels, shown in Table 1. The standard for DC charging has not yet been determined by the SAE and automobile manufacturers, so even though the SAE J1772 is capable of DC fast charging, most are only configured for L1 and L2 AC charging.

<table>
<thead>
<tr>
<th>Charge Level</th>
<th>Voltage</th>
<th>Max Current / Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 (L1)</td>
<td>120VAC</td>
<td>16A - 1.9kW</td>
</tr>
<tr>
<td>Level 2 (L2)</td>
<td>208 - 240VAC</td>
<td>80A - 20kW</td>
</tr>
<tr>
<td>DC Level 1 (L3)</td>
<td>200 - 500V DC</td>
<td>80A - 40kW</td>
</tr>
<tr>
<td>DC Level 2 (L3)</td>
<td>200 - 500V DC</td>
<td>200A - 100kW</td>
</tr>
</tbody>
</table>

L1 charging adds around 5 miles per hour of charge, making it best suited for plug-in hybrids with low electric range. It is too slow for most battery electric vehicles (BEVs). A possible use case for L1 charging would be long-term parking, such as airport garages. L2 charging can add up to 62 miles per hour of charge, making it suitable for most parking locations such as home, work, and commercial locations. The actual rate of charging is limited by the on-board controller in the vehicle. A drawing of the J1772 plug is shown in Figure 10.
The charger has 5 pins: the top two pins are hot lines (Line1 and Line2/Neutral), the bottom pin is ground, and of the remaining two pins, the left is for proximity detection and the right is the control pilot. The proximity detection circuit identifies three possible plug states using a voltage divider circuit: not connected (<1.5V), button pressed (3.0V), and connected (1.5V). The control pilot enables the vehicle’s onboard charging equipment to talk to the EVSE. It uses a square wave where the voltage defines the state and the duty cycle defines the maximum available current. For the state condition, the EVSE first sends a pilot 12 V to -12 V square wave, which the EVSE reads and responds by increasing the resistance. The EVSE also sets the duty cycle, and the EV must comply to the setting or change the duty cycle. An in-depth exploration of the charging equipment’s signaling protocol was outside of project scope.
2.4 Structural Theory

2.4.1 Load and Resistance Factor Design

In order to find the maximum possible loading on the structure in Load and Resistance Factor Design (LRFD), an evaluation of five different equations has to be performed. These expressions are

\[
\begin{align*}
U &= 1.4D \\
U &= 1.2D + 1.6L + 0.5(L_r \text{ or } S) \\
U &= 1.2D + 1.6(L_r \text{ or } S) + (L \text{ or } 0.8W) \\
U &= 1.2D + 1.6W + L + 0.5(L_r \text{ or } S) \\
U &= 1.2D + 1.0E + L + 0.2S
\end{align*}
\]

where the largest ultimate load \( U \) is used as the design load [20].

2.4.2 Loading Situations

2.5 Concrete Ballast Theory

When evaluating the concrete ballast loading situation, it was important to consider a variety of factors to ensure they will match the construction loading of this project since the manufacturer would have assumed it would be cast in place as is typically done.

2.5.1 Typical Concrete Beam

In order to check the shear and moment strength, define a concrete beam of length \( L \), height \( h \) and width \( b \), with a a weight of \( w_{\text{bs}} \), as seen in Figure 11.
Given the simplified loading situation in Figure 11, the maximum moment would be \( M = \frac{wL^2}{2} \). Assuming two pieces of reinforcement bar with total cross sectional area \( A_s \), and a clear cover distance of 3 inches. Then, if the diameter of the rebar is \( d_r \), define the \( d \) in Figure 12 as

\[
d = h - 3 - d_r. \tag{6}
\]

Assuming steel yields \( \epsilon_s = \epsilon_y \), then define the tension in the steel \( T \) as

\[
T = A_s \times (60 \text{ ksi}). \tag{7}
\]

If \( f'_c \) is the compressive strength of concrete, and \( \beta_1 \) is a constant, then \( c \) can be found as

\[
(0.85f'_c)(\beta_1 c)(b) = T \rightarrow c = \frac{T}{0.85b\beta_1 f'_c} \tag{8}
\]

Then, defining \( a = \beta_1 c \),

\[
M_n = A_s f_y (d - 0.5a) \tag{9}
\]

\[
V_n = 2\sqrt{f'_c}(bd) \tag{10}
\]

where \( M_n \) is the ultimate moment strength, and \( V_n \) is the ultimate shear strength. In order to see if the beam will hold, both of these values must be tested and the smaller of the two is then compared to the maximum shear and maximum moment.
3 Design

3.1 Site Selection

Initially, several different spots were considered for the project location. When the project was still a carport, the parking spots next to the heat plant looked like a good place for the solar carport. Unfortunately, the parking spots were right next to a diesel pump for the diesel vehicles on campus. Furthermore, there were gas lines underneath the site so there could be nothing on top of that land that made the line difficult to access. Due to these issues, the Fieldhouse West parking seemed to be a good alternative. However, due to the large economies of scale of carport structures, the project was changed to separate charging and generation. The parking lot is marked by a red circle in Figure 13. To decide the matter completely, the parking lot was still new, and any “significant change” would have triggered a zoning review.
Several spots were considered at this location for placement of the solar panels. The one requirement was that the solar panels and electric vehicle charging station would be within sight of one another. Initially, the six panels were supposed to go between Fieldhouse 502 and 504. However, at this location, there is a lot of shading from the nearby houses at the edges of the solar array, to the point where it would not be worth even installing the two outermost panels. The charger was also placed in between two parking spots at this location initially. Figure 14 shows the eventual location for the panels.
Figure 14: Overhead view of system location from Bing Maps

The location out front of Fieldhouse 502 was decided on using solar pathfinder data. Given the large number of trees and other sources of shading in the area, it was difficult to find a spot with minimal shading. With the new solar panel location, the charging station was also shifted to its new location to maintain the line of sight. It was placed one spot over from the ADA parking spaces so there would not be any requirements attached to using the charging station.

Other locations on campus were considered as well, although they were all dismissed for a variety of different reasons. The Fieldhouse West parking lot location meant the solar panels would be very visible to anybody going to the Matchbox or walking around that side of campus. Many visitors pass through as well, which would increase exposure. Whittier parking lot next to the Science Center, shared some of these traits as there is visitor parking. However, there is much less foot traffic in the area which would have reduced the overall exposure. Any construction also would have created a much larger disruption to daily traffic in Whittier parking lot. The largest factor in deciding against Whittier, though, was the possibility of construction during the design life of the project. The parking lot by the water tower was
dismissed for visibility reasons, as were most other parking areas on campus.

3.2 Energy Modeling

*Research question:* How much solar do we need to completely offset energy used for charging vehicles?

Because the motivation for this project was to examine the potential of emission free transportation for Swarthmore College, we wanted to understand the energy output of our solar array and how many electric vehicle miles it would be able to offset. Range anxiety is one of the central issues that limits electric vehicle adoption, and institutions have not invested in vehicle service infrastructure because of low demand. This chicken-and-egg problem needs to be resolved before large scale fuel-switching and GHG reduction can be achieved in the light-duty vehicle transportation fleet.

The purpose of this section is to describe the energy modeling effort, explain the model’s results, and reflect on the research question.

3.2.1 System Advisor Model (SAM)

We chose to use the National Renewable Energy Laboratory’s (NREL) System Advisor Model (SAM) to simulate PV performance and compare against forecasted EV charging demand. The model is available for free download on the NREL website, where helpful documentation is also available. In addition to solar PV, SAM also can be used to model high concentration PV, wind, biomass, geothermal, solar water heating, and concentrating solar power (parabolic trough, power tower, linear Fresnel, dish Stirling) technologies. The model was developed in part by a Swarthmore alumnus, Aron Dobos ’06.

SAM consists of a user interface, calculation engine, and programming interface. The user interface is the part of SAM that you see, and provides access to input variables and simulation controls, and displays tables and graphs of results. SAM’s calculation engine performs a time-step-by-time-step simulation of a power system’s performance, and a set of annual financial calculations to generate a project cash flow and financial metrics. The programming interface allows external programs to interact with SAM.

The model that we used – the detailed PV model – calculates a grid-connected PV system’s electrical output using separate module and inverter models. The detailed PV model estimates losses due to the effect of temperature on module performance, and has options for calculating shading and other losses in the system. From the user
interface, the user simply inputs the site location, array design parameters, equipment models, financial assumptions, project and operational costs, and electricity tariff schedules. SAM then accesses the relevant hourly (8760) weather data from the National Solar Radiation Data Base (TMY3), equipment specifications from its database of commercial equipment, and tariff rates from the OpenEI U.S. Utility Rate Database. With the necessary data in place, SAM’s calculation engine performs a time-step-by-time-step simulation of a power system’s performance, and a set of annual financial calculations to generate a project cash flow and financial metrics. The user can then go back and change model inputs to evaluate how the model responds to changes to key inputs, such as tilt angle for solar arrays or federal incentives for system payback. SAM also has further analysis tools to easily conduct parametric and sensitivity analysis, perform stochastic simulations, and run P50/P90 analysis.

### 3.2.2 Modeling Solar Generation

To model solar generation, we used the following inputs for our 1.68 kW nameplate solar array:

- **Location and Resource:** Philadelphia International Ap (TMY3), Perez transposition model, Beam and diffuse irradiance used for calculation

- **Module:** SolarWorld SW 280 mono, NOCT ground or rack mounted, One story building height or lower

- **Inverter:** Enphase Energy: M250-60-2LL-S2x(-ZC)(-NA)240V

- **System Design:** 1 module per string, 6 strings in parallel, 6 inverters; fixed tilt at 38 degrees, azimuth 180 degrees, 0.3 ground coverage ratio

- **Shading:** Solar Pathfinder or SAM 3-D Shading Models (depending on case)

- **Losses:** Soiling 5%, Diodes and connections 0.5%, DC wiring 2%, AC wiring 1%

- **Degradation:** 0.5% per year

We used two methods to estimate shading losses: the Solar Pathfinder tool, and SAM’s built-in 3-D shade modeling tool. The Solar Pathfinder measures shading for potential locations by comparing a reflection of potential obstructions to a sun path diagram of the local solar window. It does this by overlaying a reflective dome
over a latitude-specific sunpath diagram. The user then can take a picture of the overlay, and trace out the horizon’s shading using its proprietary software. The 8760 shading estimates from the site can then be uploaded to the SAM model’s Shading tab for solar simulations. The Solar Pathfinder estimated annualized shading effects of 20.05%. An image of the Solar Pathfinder shading results is shown in Figure 15 for reference. The complete Solar Pathfinder report for the final site location is included in Appendix C.

Figure 15: Solar Pathfinder photograph and sun path diagram

We also created a 3-D model of the various shading obstructions at the site using SAM’s shade modeling tool. By overlaying a satellite image view of the site with obstructions such as trees of different shapes, poles, and houses, the tool allows you to build a 3-D model of local shading effects. The one drawback of the tool is that there are no physical scale parameters – all the shapes are meant to be sized relative to one another. Nonetheless, the 3-d shading tool was valuable in generating another estimate of shading effects: 10.72%. Two images of the 3-D shading model are shown in Figure 16.
Using these two shading estimates, we were able to use the SAM’s parametric analysis feature to analyze the optimal tilt angle under shading. Due to the large trees obstruction the southeast and southwest radiation flanks, we had a hypothesis that the optimal tilt angle would be shallower than latitude (around 30 degrees). Our reasoning was that since those large trees limit solar radiation near sunrise and sunset and would have even more pronounced shading effects in the winter when the sunpath is lower in the sky (greater zenith angle), we would be better off from maximizing production in the summer with a shallow tilt. We were able to test whether or not this was true using the SAM model, and the results are shown in Figure 17.
Figure 17: SAM parametric analysis of tilt angle effects on annual PV output

As shown, the optimal tilt angles were 36 degrees for the Solar Pathfinder model and 38 degrees for the 3-D shade model. According to parametric simulations, our intuition was correct, but our estimate overshoot the optimal adjustment from latitude. Furthermore, Figure 17 shows that overall, the annual solar output is not very sensitive to changes in tilt angle near the optimal angle. In fact, a 3 degree range around the optimal angle decreases annual output by less than 3 kWh. Given that this model is forecasting solar output with a several uncertainties (future weather, actual losses, and more), this is not a significant amount of power. Thus when we constructed the solar array, we aimed for a tilt angle of 38 degrees, with a uncertainty range of 2 degrees.

Overall, these two shading estimates drove two branches of simulation cases. At the time of report writing, there was not enough operational data to determine which shading model was more accurate.

3.2.3 Estimating Electric Vehicle (EV) Charging Demand

We set out to estimate vehicle charging demand for two types of drivers: an average commuter (Swarthmore staff or faculty), and a Swarthmore Public Safety vehicle. These two drivers represent the limits of EV charging demand: one would only require charging to offset its commuting mileage, the other would require charging to offset...
its entire mileage. First, we derived daily load shapes from transportation survey data, adapting a methodology from a 2011 study by the Electric Power Research Institute [5]. These load shapes are generated from a simple EV charging model based on daily trip information from the 2009 National Household Travel Survey (NHTS). We used the information on trip start and end times, start and end locations, and trip length to create a demand curve for charging, constraining charging to certain generic locations (home, work, mall, etc.). Assuming a simple immediate charging strategy (charge as soon as parked in eligible location, at Level 2 average rate of 6.6 kW), a constant vehicle efficiency of 0.311 kWh/mi and constant battery size of 30 kWh, we were able to construct EV charging demand for each vehicle. A large number of vehicles (100,000) were aggregated to factor in the variability in trip arrival and departure times, and then the load was averaged on a per vehicle basis and normalized for total mileage. By constraining charging availability, we were able to generate different daily load shapes for different types of drivers. Shown in Figure 18 is the hourly normalized charging demand for at-work and at-home charging for a working weekday.

![Normalized EV load curve by charging location on weekdays](image)

Figure 18: Normalized EV load curve by charging location on weekdays

The darker at-home charging demand peaks between 5:00pm and 8:00pm, whereas the lighter at-work charging demand peaks between 7:00am and 10:00am. This is intuitive because most survey responders arrive at work in the morning and plug in their vehicles until fully charged, resulting in a workplace EV demand peak in the
morning. Similarly, most survey responders arrive home in the late afternoon and plug their vehicles in until fully charged, resulting in a home EV demand peak in the evening. Though these load curves depict simplistic charging strategies, they are a decent estimate of potential EV behavior at Swarthmore in the absence of a EV charging pricing program or charging schedule.

Next, we obtained national commuting mileages from the 2009 NHTS [2], 2014 Swarthmore commuting and Public Safety mileages from Sustainability Director Laura Cacho. These values are listed in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Roundtrip Commute (miles)</th>
<th>Annual Mileage (miles)</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swarthmore commuter (2014 Cacho)</td>
<td>8</td>
<td>2,080</td>
<td>380</td>
</tr>
<tr>
<td>National commuter (2009 NHTS)</td>
<td>12</td>
<td>3,143</td>
<td>150,147</td>
</tr>
<tr>
<td>Public safety cruiser (2014 Cacho)</td>
<td>50</td>
<td>18,404</td>
<td>2</td>
</tr>
</tbody>
</table>

Finally, we scaled the normalized vehicle demands to equal the annual vehicle mileages listed in Table 2. It seems reasonable to assume that commuters’ charging patterns resemble workplace charging load shape, and a Public Safety vehicles charging patterns resemble the home charging load shape. Shown in Figure 19 is the hourly demand for different drivers for a working weekday.

![Hourly demand for different drivers on a weekday](image)

Figure 19: Scaled EV load curve by vehicle type
The Public Safety vehicle demand dwarfs the commuter demand due to its relatively astronomical annual mileage. Though these EV load shapes are by no means perfect, they are a decent estimate of when certain types of drivers will be charging and annualize to the total mileage numbers. Therefore, they should be a good estimate of the annual energy needed to charge commuters and Public Safety electric vehicles with the constant driving patterns. Another assumption was that mileage, vehicle efficiency and battery sizes would stay constant over time. These load shapes were then annualized to 8760 load numbers and inputted into the SAM model as the commercial PV system’s electric load data. This enabled cost estimates for the electricity needed to charge vehicles, as well as enabling a side-to-side comparison with annual solar generation.

3.2.4 Modeling Results

The SAM is free to download and its functionality is contained with its user interface, so we limit our discussion of the model here to the input cases and overall results. The detailed reports for each SAM case is included in Appendix D.

Because the energy output of the solar array is independent of the electric vehicle charging load, only two cases were run to determine the annual energy from solar: one for the 3-D shading model, and one for the Solar Pathfinder shading model. The forecasted annual energy output was then compared with the annual EV charging demand for different drivers. The projected annual energy for the two cases and national and Swarthmore commuter energy requirements are shown in Figure 20. The Public Safety vehicle annual energy demand is not shown because it would dwarf the other numbers.
Figure 20: Annual Energy Generated and Consumed by Commuters (Year One)

Some simple calculations yield to the following interesting conclusions. Over one year, our solar PV system can:

- Completely offset 6,359–7,130 miles, which is the equivalent of
  - 3.0–3.4 Swarthmore commuters
  - 2.0–2.3 national commuters
  - 0.3–0.4 Public Safety cruisers

- With similar solar equipment and deratings,
  - 1.8–2.0 panels are needed to offset one Swarthmore commuter
  - 2.0–2.7 panels are needed to offset one national commuter
  - 15.4–17.4 panels are needed to offset one Public Safety cruiser

- Over its 25 year lifetime, our system can generate between 48.3–52.2 MWh of solar energy, the equivalent of 155k–168k miles of EV transportation.

The monthly energy generated under the 3-D shading model and driver types is shown in Figure 21. As mentioned, the Public Safety vehicle demand is several times greater than the monthly generation available. However, the generation is able to comfortably offset the energy demand of 2 commuters in each month of the year.
3.3 Electrical System Configuration

The configuration of the electrical equipment began with the purchase of solar PV and EV charging equipment. We communicated with Facilities and Maintenance to ensure that our equipment would be compatible with the electrical service at the site—240 V, single-phase. Afterwards, we developed the electrical diagrams based on conversations with Bill Maguire, the College electrician, and his staff.

3.3.1 Electrical Equipment Selection

Prof. Everbach reached out on our behalf to Michael Matotek of Open Sky Energy, a solar installation company located in Swarthmore. The solar panels, 6 SolarWorld SW280 Mono, and microinverters, 6 Enphase M250s, were selected with his recommendations. We chose monocrystalline silicon panels because they have slightly higher efficiencies than polycrystalline counterparts, and we wanted to maximize solar output over the small area of a carport (at the time). We went with microinverters because there are obstructions (trees) everywhere on the Swarthmore campus, so we wanted to make sure that MPPT was available on each module. The Enphase microinverters also came with an Envoy Energy Monitoring Unit, which tracks individual module output using power-line communications technology and streams the data to a public website hosted on Enphase’s servers. This would easily enable detailed performance monitoring and become a resource for those interested in installing solar on campus. At the time of writing, this website can be accessed at:
Though there are guides and protocols to building a SAE J1772 compatible EV charger (such as the OpenEVSE project [17]), this was outside of project scope, and we chose to purchase a stock electric vehicle charging system. We went with two Clipper Creek HCS-40 charging stations, mounted on a pedestal with two additional 120 V GFCI outlets. This was the most inexpensive dual charger on the market and with two outlets, it could charge a maximum of six EVs at once: two at Level 2 rates, and four at Level 1 rates (if they had onboard Level 1 chargers, which most EVs actually do).

We also needed to monitor and collect data on PV output and EV charging load. If six EVs are charging at once, the EV charging load could theoretically reach 128 A, which is exceeds the limit on most household main service breakers. Because EV loads can potentially become large loads on the system, we wanted to be able to monitor usage over time accurately and allow further study of EV charging at Swarthmore. Thus, we decided to use a networked Siemens Digital Energy Monitor (D.E.M.) to measure energy used for EV charging. The D.E.M. is basically a current transducer that has networking capabilities and can sync with the Siemens energy management system. This enables long-term monitoring of EV charger usage, and even allows people to view real-time power draw on the Facilities website. Tom Cochrane and Ralph Thayer of Facilities provided one of these meters and helped us set it up. Since the solar array already had a networked monitoring unit in the Envoy EMU and it would be generating relatively small amounts of current, we decided that it did not need its own D.E.M.. However, we did want it to be eligible for solar renewable energy credits (SRECs) in the future, which requires it have a revenue grade meter. Open Sky Energy provided us with one of their standard, non-networked revenue grade meters, which we installed with Facilities.

3.3.2 Installed Electrical System

The final electrical system diagram is shown in Figure 22. On the top right are our six 280 W modules, each with a microinverter, connected in series through an Enphase Engage trunk cable. This cable has built-in ports connections for microinverters to clip in to, and will always provide 240 VAC at a level of current that depends on the array output (maxing out at 7 A). The trunk cable is then joined to 10-AWG wire, which is routed underground through PVC pipe 18 inches underground between Fieldhouse #500 and #502. The wire then goes into an outdoor disconnect switch to shut off the PV array. Then, the two hot lines (240 V) are run through the
revenue-grade meter, and then into the basement of #502, where it is back-fed onto a 15 A double-pole breaker and surge protector. On the same distribution panel, the Envoy EMU is plugged into a 120 V outlet and reads microinverter performance over the neutral line using power-line communications. It streams this to the Internet to Enphase’s servers and Enlighten webpage, where users and the public can monitor system output.

On the other side of the system, two HCS-40 level 2 chargers and two 120 V GFCI outlets are installed on a pedestal at the back of #502. Because the need to travel over 100 feet to the outdoor distribution panel, we chose to use 6 and 10-AWG wire to limit the voltage drop over the long distance, though for the ampacity rating we only needed 8 and 12-AWG. A simple voltage drop calculation is shown:

\[
V_{\text{drop}} = I_{\text{op}} \times R_e \times L
\]

\[
V_{\text{drop}}(8\text{AWG}) = (40\text{A}) \times (0.6282\Omega/\text{kft}) \times (0.2\text{kft}) = 5.03V = 2.10\%
\]

\[
V_{\text{drop}}(6\text{AWG}) = (40\text{A}) \times (0.3951\Omega/\text{kft}) \times (0.2\text{kft}) = 3.16V = 1.32\%
\]

Even though 2.10\% is less than the NEC recommend maximum drop of 3\%, we determined it would be best to increase the conductor size. All four lines are routed through a Siemens current transducer to measure energy draw of the EV chargers. Then, each HCS-40 is energized through a 40 A double pole breaker, while each 120 V outlet is energized using a standard 15 A single pole breaker. The Siemens D.E.M. is then networked via a CAT5 Ethernet cable that connects through #506.
3.4 Carport Structural Design

This subsection outlines the design process of scalable structural carport system. Designing this structure was one of the secondary objectives of this project.

Before beginning the design process, it was necessary to find the design loading of the structure. Once all of the loading considerations from LRFD were considered, the largest value was then used as the loading on top of the solar panels. From this, loading situations were created according to the structural specifications, as described in Section 2.4.2. Each of these were then passed into the code defined in Appendix A to see if they would withstand the loading situation. Different sections were attempted to minimize the weight.
3.4.1 Load Calculations

In order to find the maximum loading, the live loading was assumed to be zero as the snow load during the winter should cover any live load situation for maintenance when there is no snow on top of the structures. The base ground snow load factor, \( P_g \) is 25 psf [21]. As it is a mildly sloped roof, the \( P_s \) has to be found, where \( P_s = C_s \times P_g \) and \( C_s \) is the roof slope factor [21]. In order to find \( C_s \), it is first necessary to determine \( C_t \) from ASCE Table 7-3, where \( C_t \) is the Thermal Factor [21]. Since it is an open-air structure, \( C_t = 1.2 \). It is therefore considered a cold roof. Using ASCE 7.4.2, \( C_s = 0.98 \) with a roof angle of 15.67°. Therefore, the snow load is

\[
P_s = 0.98 \times 25 = 24.5 \text{ psf}.
\]

Next calculating the wind load, the design wind speed is 90 mph [21]. Therefore using U.S. customary units, the static wind pressure \( q_s \) is \( 0.00256v^2 \) where \( v \) is the basic wind speed. However, the design wind pressure must consider several other factors so that the magnitude of the velocity wind pressure \( q_z \) is

\[
q_z = q_s I K_x K_{zt} K_d,
\]

where \( I \) is the importance factor, \( K_x \) is the velocity pressure exposure coefficient, \( K_{zt} \) is the topographic factor, and \( K_d \) is the wind directionality factor [20]. Since the structure is open and in a parking lot which may carry some foot traffic as well as have vehicles at risk, the importance factor should be 1. The importance factor should not be larger, as failure would not cause a large loss of life. Next, the exposure category for finding \( K_x \) should be B, as it is a suburban area with low structures. With this exposure category, and a height below 25, \( K_x = 0.70 \) [20]. The topographic factor \( K_{zt} \) would simply be 1 as the structure would be located on flat ground. Finally, the wind directionality factor \( K_d \) would be 0.85 for the main wind force-resisting system. Overall, using Equation (11)

\[
q_z = 0.00256 \times (90 \text{ mph})^2 \times (1)(0.70)(1)(0.85) = 12.338 \text{ lb/ft}^2.
\]

From this, the design wind pressure is

\[
p = q_z \times G \times C_n
\]

where \( G \) is the gust factor and \( C_n \) is the net pressure [21]. The gust factor is 0.85 as
it is a rigid structure. The wind flow should be assumed to be unobstructed, so with a 15.67° roof, then $C_N$ is -1.1 or 1.1 depending on whether the wind is hitting the underside or the topside of the angled tee [21]. Plugging back into Equation (12),

$$p = 12.338(0.85)(-1.1) = -11.536 \approx -11.54 \frac{\text{lb}}{\text{ft}^2}.$$  

$$p = 12.338(0.85)(1.1) = 11.536 \approx 11.54 \frac{\text{lb}}{\text{ft}^2}$$

This means that the total load on the panels will be either of the two below:

$$w = 24.50 + 11.536 = 36.04 \frac{\text{lb}}{\text{ft}^2}$$

$$w = -11.54 \frac{\text{lb}}{\text{ft}^2}$$

The design load for the panels on a two rail system like in this model is 113 psf downward and 64 psf upward [30]. This leads to a factor of safety of 3.14 for the downwards force and 5.818 for the upwards force.

Each of these panels is 39.5 lbs, and each is 65.94 in by 37.44 in or 5.495 ft by 3.12 ft. Therefore the area of one panel is 17.144 ft$^2$. So each panel adds 17.144(36.04) + 39.5 = 657.4 lbs to the design load of the structure of downwards force or 17.144(11.536) - 39.5 = 158.27 lbs of upwards force.

### 3.4.2 Final Revit Design

The final Revit design was an angled-tee shape that is intended to face southwards to maximize the photovoltaic output. Due to the limitations of any joint between the column and the girders, the angle was kept to just 15.67°. Without this, the moment would have exceed reasonable design constraints. Joint design was beyond the scope of the project. Because many other structures use shallower tilt angles than this, the chosen angle seemed reasonable [14].

Each of the the components of the Revit model were tested using the code Python code from Appendix A. The program accepts the various section and material properties, the maximum moment, and the maximum shear as inputs, and implements the American Institute of Steel Construction (AISC) tests for flexure, shear, and lateral torsional buckling [23]. This made it much easier to test various different sections to try to minimize the weight, which is often a proxy for cost. A side view of the Revit model is in Figure 23.
Complete coverage of the six parking spaces is achieved with this design. A steeper angle would have actually required more solar panels to fully cover the parking area, which would have significantly increased the weight on the girders and the columns. The vehicle models are from user Bradley911 on Revit City. A full rendering of the parking lot is in Figure 24. This rendering took 3.5 hours to process. The spaces in between carport structures and the parking spots are to the correct dimensions. The height of the lower side of the angled-tee was 11 feet to accommodate most vehicles. This was the same height used by Solaire Generation in their carport designs [14].
To give a better idea of what the structure might look like when constructed, a first person view from about 6 feet in the air looking down at the ground is in Figure 25. There is one charging station between four parking spots. While the station used in our project only supported 2 electric vehicles, an online tool would be able to warn people that other vehicles are done charging. Then people can come by at lunch or another appropriate time and switch it to another vehicle.

3.5 Solar Structure Specifications and Requirements

The manufacturer included reasonably specific instructions on how the structure is assembled, but their concrete ballasts did not account for construction loading. While the manufacturer intended for the ballasts to be cast in place and then never moved again, geographical limitations meant it was important to be able to lift the structures within a few few days of pouring so that the project could be completed within the projected time line.

Figure 25: First Person View of Carport
3.6 Lifting The Concrete Ballasts

Due to the site location, it was impossible for a concrete truck to reach the site. For this reason, the beams were cast next to the heat plant on a relatively flat surface to be later transported to the site using a backhoe. Several different designs were considered to handle the construction loading, including using hooks made from reinforcement bar, slots at the bottom of the beam for a forklift, and a threaded rod attached to a lifting eye on one side and welded to the reinforcing steel or attached to a steel plate on the other. Throughout these calculations, only the 28 day strength of concrete was considered as too many factors would have affected the 7 day strength to make an accurate estimate.

3.6.1 Reinforcement Steel (Rebar) Calculations

Two pieces of #4 rebar were used in the top section of the beam where the Whitney stress block shows there would be tension. To see if the two pieces of rebar would be sufficient, Equations (9) and (10) were used. The diameter of the rebar is $d_r = 0.5$ in.
Plugging into Equation (6),

\[ d = 12 \text{ in} - 3 \text{ in} - 0.5 \text{ in} = 8.5 \text{ in}. \]

If \( f'c \) is 3500 psi, \( \beta_1 \) is the standard value of 0.85, \( A_s = 0.2 \text{ in}^2 \), and \( b = 13 \text{ in} \), then plugging this all into Equation (8) gives a \( c \) value of

\[ c \approx \frac{(2 \times 0.2 \text{ in}^2)(60000 \text{ psi})}{(0.85)(13 \text{ in})(0.85)(3500 \text{ psi})} = 0.7301 \text{ in}. \]

Since \( a = \beta_1 c = 0.85(0.7301 \text{ in}) = 0.6206 \text{ in} \), it is now possible to find the ultimate moment \( (M_u) \) and ultimate shear \( (V_u) \) that the design can withstand:

\[ M_u = (2 \times 0.2 \text{ in}^2)(60 \text{ ksi})(8.5 \text{ in} - 0.5 \times 0.6206 \text{ in}) = 196.55 \text{ kip \cdot in} \]
\[ V_u = 2 \times \sqrt{3500 \text{ psi}(13 \text{ in})(8.5 \text{ in})} = 13.074 \text{ kips} \]

Clearly the beam at 28 days will be able to hold significantly more than its self-weight without any issues. Using the loading situation described in Figure 11, the self weight would translate to \( w = 162.5 \frac{\text{lb}}{\text{ft}} \). For the shear and moment calculations, \( w_{V_u} = 4683 \frac{\text{lb}}{\text{ft}} \) and \( w_{M_u} = 4203 \frac{\text{lb}}{\text{ft}} \).

### 3.6.2 Anchor Bolt Calculations

In the end, the hooks concrete ballast was lifted using a lifting eye attached to a concrete anchor. This concrete anchor needs to be able to support up to 900 lbs. Using 150 \( \frac{\text{lb}}{\text{ft}^3} \) as the weight of concrete, the cross section of the beam is 12 in by 13 in. Since the beam is 67 in long, the total volume is 6.049 \( \text{ft}^3 \). Therefore, the anchor must be able to hold 907.4 lbs.

When looking ACI 318-11 Appendix D, the code describes three types of failures that apply to this situation. Figure 27 shows the three loading situations. The first is the tensile failure of the steel anchor bolt, which is found in Section 5.1 in Appendix D. The second is that the anchor bolt would be pulled out of the concrete, which is found in Section 5.3. The third and most likely, is that there would be concrete breakout found in Section 5.2.
First checking for steel failure, the diameter of the threaded rod was $\frac{5}{8}$ in. Using $f_y = 60$ ksi, the anchor bolt has an ultimate strength of

$$N_{sa} = (60 \text{ ksi}) \left( \pi \times \left( \frac{5}{8} \right)^2 \text{ in}^2 \right) = 60 \times 0.3068 = 18.408 \text{ kips}$$

Since the load is only 0.9074 kips, the factor of safety is 20.3 and the steel will not fail [1].

The next failure mode is concrete breakout strength. The nominal concrete breakout strength from Appendix D is

$$N_{cb} = \frac{A_{Nc}}{N_{Ncb}} \psi_{ed, N} \psi_{c, N} \psi_{cp, N} \psi_{bf, N} N_b.$$  \hspace{1cm} (13)

First, $N_b$ is the basic concrete breakout strength of a single anchor in tension, assuming the concrete has cracked and is defined in Appendix D as

$$N_b = k_c \lambda_a \sqrt{f'c h_{ef}^4}.$$  \hspace{1cm} (14)

Since the anchors are cast in, $k_c = 24$. $\lambda_a$ is the lightweight concrete factor, which would simply be 1, since the concrete was regular strength. $f'c$ is the compressive strength of concrete, which was 3500 psi in this case. Finally, $h_{ef}$ is the distance from the top surface of the concrete to the top of the plate on the bottom which was 7 in. Plugging into Equation (14),

$$N_b = (24)(1)\sqrt{3500 (7)^{1.5}} = 26.30 \text{ kips}.$$  

Next, $\psi_{ed, N}$ is the modification factor for edge effects for single anchors or anchor
groups loaded in tension [1]. If $c_{a,min}$ is the distance from the center of the bolt to an edge, then because $c_{a,min} < 1.5 h_{ef}$,

$$
\psi_{ed,N} = 0.7 + 0.3 \frac{c_{a,min}}{1.5 h_{ef}}.
$$

(15)

ACI 318 Appendix D assumes a fracture angle of $35^\circ$, but if there is not enough space to the edge for a crack to fully form, then it must be adjusted by this factor. Plugging into Equation (15), $\psi_{ed,N} = 0.8857$ [1].

Next, $\psi_{c,n}$ is a modification factor for regions where there will be no cracking at service load levels. From 3.6.1, it is clear that no cracks will form when lifting the concrete. Since it is also a cast-in anchor, $\psi_{c,n} = 1.25$ [1].

The final modification factor, $\psi_{ep,N}$ only applies to post-installed anchors, so $\psi_{ep,N} = 1$ [1].

Now, $A_{Nc}$ and $A_{Nco}$ must be found. ACI 318 Appendix D defines these areas in Fig. RD.5.2.1 to be

$$
A_{Nco} = 9 h_{ef}^2
$$

$$
A_{Nc} = (c_a + 1.5 h_{ef})(2 \times 1.5 h_{ef})
$$

Plugging in, $A_{Nco} = 441$ in$^2$ and $A_{Nc} = 357$ in$^2$. Finally, plugging everything into Equation (13),

$$
N_{cb} = \frac{357}{441} (0.8857)(1.25)(1)(26.30 \text{ kips}) = 23.57 \text{ kips}.
$$

This is actually larger than the $N_{sa}$, so the maximum loading is still 18.41 kips.

The third and final failure situation the anchor pullout. In ACI 318 Appendix D, the nominal pullout strength for a single cast-in anchor is

$$
N_{pu} = \psi_{c,p} N_p.
$$

(16)

The basic pullout strength of a single headed bolt is

$$
N_p = 8 A_{brg} f'_c.
$$

(17)

The bearing area is $A_{brg}$. It was not possible to access the appropriate code for free, so the bearing area is simplified to just be the area of the steel plate which is 5 in by
5 in, so it is 25 in\(^2\). Plugging values into Equation (17),

\[ N_p = 8(25)(3500) = 700 \text{ kips.} \]

Next, \( \psi_{c,P} \) is the modification factor for whether there is any cracking at service loads. Since there is no cracking, \( \psi_{c,P} = 1.4 \). Plugging this all into Equation (16),

\[ N_{pn} = 1.4 \times 700 = 980 \text{ kips} \]

This number is very large, due to the size of the steel plate at the base of the threaded rod. Overall, if the concrete anchor bolt were to fail, it would be due to a steel failure as long as the concrete had its full 28-day strength.

4 Construction and Implementation

4.1 Concrete Formwork

In any project involving concrete, typically engineers will create wooden formwork to contain it while it sets. From the earlier design, the ballasts have to be 67 inches long, 13 inches wide, and 12 inches deep. The ground-mounted array's design necessitates three concrete ballasts, each weighing about 900 pounds. In order to create this, formwork had to be built that would be able to withstand the hydrostatic pressure of wet concrete. The formwork was made of pieces of \( \frac{3}{4} \) in plywood and two by fours. Figure 28 displays the sides made of plywood and two by fours used as supports with screws through the bottom sheet and the side sheets.
Figure 28: Top and Side View of Concrete Formwork

Figure 29 shows the ends of the formwork. Small pieces of two by fours that had been cut in half were used to make the structure more rigid. Without the small pieces that attach the side and end panels, both were able to wobble significantly.

Figure 29: Front View of Concrete Formwork

In order to construct the formwork, every piece of plywood that would be exposed to concrete was first wrapped in polyethylene (poly) wrap. This would make removal of the formwork much simpler and would make the sides of the concrete much
smoother. All of the bottom two by fours were then attached in the appropriate positions so that the plywood making up the edges could be inserted. These were then attached using three screws to each of the pieces of two by four, which can be seen in Figure 30. Cinder blocks were used to flatten out the bottom piece while attaching the sides. Once the sides were attached, they kept the bottom piece reasonably flat without the cinder blocks.

Figure 30: Completed Formwork with Cinder Blocks

4.2 Site Preparation

To prepare the site for both the electric vehicle charger and for the ballasted solar structure, the site needed to be evaluated for possible complications from underground pipes and conduits, and then prepared to connect the electric vehicle charger and the solar panels to the grid. Since the structure did not need a foundation, it was unlikely there would be any direct problems with other utilities that were buried deeper in the ground. However, it is important for services like natural gas to be accessible from the surface with little notice, so the location of these lines had to be taken into account.

Initially, Tom Cochrane gave a rough estimate of where different utilities would be. Once everyone cleared the prospective site for the solar array, the electric vehicle charger, and for the trench location, the construction began according to the plans.
in Figure 26. Since there was over 200 feet of trenching to do, facilities rented a trenching machine in Figure 31. Kenneth McNeal trenched the long section between the distribution panel to the electric vehicle charger. While he was able to trench part of the connection from Fieldhouse Lane #502 to the PVMini site, it was still necessary to dig about 20 feet by hand.

![Trenching Machine](image)

Figure 31: Trenching Machine

It was necessary to tunnel underneath the sidewalk three times, twice underneath the wide sidewalk and once underneath the small section in Figure 31. The wider section of the sidewalk was 5 feet wide, and the concrete goes to about 6 inches deep, under which there is about 4 inches of gravel followed by soil. The sharp end of the digging bar was used to break up the soil and loosen the stone, after which a digging shovel was used to move the dirt and rock onto a pile next to the trench. The final tunnel was about 1 foot by 1 foot, as seen in Figure 32.
PVC pipe was placed in all of the long trench and it was back filled to ensure that nobody could fall into the trench and injure themselves. The ends were kept open as the connections were not finished yet and plywood was placed over the holes to prevent any unintended injuries. After several days, the rest of the trench was completed using a pickaxe, a transfer shovel, and a digging shovel. After using the packaging to level the trench so the PVC pipe would lie flat, it was placed into the trench as seen in Figure 33. Then the trench was backfilled, mostly using a rake as the soil was compressed into the grass as seen in Figure 34.

Figure 33: Pipe in the Trench
Figure 34: Tony Back Filling with a Rake

Plywood was cut to the size of the charging station base, which was then served
as an outline to cut the asphalt along a rectangle using a diamond-bladed circular saw, as seen in Figure 35.

![Figure 35: Bill Maguire Cutting Asphalt](image)

Asphalt was broken up with a Hilti rotary hammer drill and removed with shovels, as depicted in Figure 36. The square hole was dug to a depth of 3 ft, which is the necessary amount to prevent frost heave. While digging, an unknown pipe was encountered and was left in place. There was also a concrete lip on the sidewalk that extended 18 inches deep which it was necessary to dig underneath. The tunnel was then completed using the digging bar and post hole digger seen in Figure 37.
4.3 Concrete Preparations and Pouring

Before pouring the concrete, it was necessary to manufacture the concrete anchors, the reinforcing steel cage, and the mortar supports. The concrete anchors would be used after six days to pick up each concrete beam. A 10,000 pound lifting eye would be attached to \( \frac{5}{8} \) in threaded rod that would be cast in the concrete. To provide the anchoring, a steel plate was cut to 5 in by 5 in, and a hole was drilled into the center of it and threaded. The plate was then screwed onto the rod, and a locknut was screwed onto the bottom side to ensure the plate would not be able to move downwards. Figure 38 shows the final anchor construction.
For each of ballast, reinforcement cages had to be built as well to hold the rebar. In order to do this, #3 rebar was bent into a square shape and then tied using 22 gauge wire. While this was reasonably tight, there was some still wobble which meant it was necessary to hold the rebar cage in place during the pour. Figure 39 shows the reinforcement cage sitting in the formwork. In order to hold up the rebar, small 3 in cubes of mortar were made using a mix of 3 parts sand to 1 part portland cement. In the end, a total of 3.3 lbs of portland cement were used, along with 9.9 lbs of coarse sand. Formwork was made for each cube, and they were allowed to cure for two days before the pour. Figure 40 shows the mortar curing in their formwork.
concrete anchor is actually screwed into the top of the side panels in order to keep them from bowing out due to hydrostatic pressure.

Figure 41: Everything In the Formwork Before Pouring

On pour day, everything was set into place to prepare for the arrival of the concrete truck. The concrete formwork was placed next to the heat plant. In total, about 6,000 lbs of concrete was used. When the truck arrived, the spout was placed into position and the concrete was dumped into the forms and the holes. Once the concrete was poured into the ballasts, the sides were hit with a metal rod to prevent honeycombs from forming that would be unattractive. Figure 42 shows the wet concrete in the forms.
The concrete truck then moved up to Fieldhouse west and the concrete was poured into the holes that we dug. This was done to keep the concrete sidewalk from cracking. Figure 43 shows the concrete pouring into the hole. Figure 44 shows the concrete vibrator which was used to help push the concrete into the tunnels. A template of the stand’s base was put on top of the concrete hole and used to align 4 J bolts that would sit in the concrete.
4.4 Moving the Ballasts and Building the PvMini

After about a week, the forms were removed and a lifting eye was screwed on to the threaded rod. A strong rope was attached to a large hook. The hook was attached to the lifting eye, and a large forklift was used to pick up each concrete ballast. They were then moved into position on two pieces of wood so they could be carried on the forks of the forklift. In Figure 45, the forklift is moving each of the ballasts to the site.

![Figure 45: The Forklift Moving the Ballasts](image)

At the site, it was necessary to use a backhoe to move the ballasts into position, because the forklift would have gotten stuck in the soil. A gravel pad had been installed beforehand by grounds, and white marks on the gravel pad specified the location of each ballast. Figure 46 shows how a perlin was used to make sure each ballast was in line, with the backhoe in the background to move it all.
After the ballasts were moved into position, the struts for the PvMini were placed on the structure, and the appropriate spots for the connections were marked with a marker. These spots were drilled into using the Hilti rotary hammer drill and then expansion bolts were installed to anchor the structure to the concrete. The struts were then installed according to the directions which were very clear and easy to understand. The only issue that arose was the leveling of the ground. It dipped on the backside of the middle ballast, so that the structure was about half an inch too short to connect to the perlins. To fix the issue, another piece of 1 in square aluminum tubing was cut to the appropriate length and then the appropriate holes were drilled. Afterwards, the perlins attached fine, and the completed structure without solar panels is in Figure 47. On the back, cross bracing was attached to both spans. The bracing was just quarter inch thick stock aluminum with one side drilled. The other side was drilled on-site so it would fit tightly.
Next, the Enphase M250 microinverters had to be attached to the structure. In Figure 47, there are small little attachments on the perlin. These are used to attach the solar panels to the structure. Each of these was spaced correctly, and then zip screws were used to attach the microinverters in the middle of where each panel would go. Figure 48 shows how each attach.

Finally, the solar panels were attached to the structure. Each of the small attachments on the perlins screws down and a lip extends over the panel, holding it to the
structure. The panels slotted in easily and Figure 49 is a picture of the final structure before hooking everything up.

![Figure 49: PvMini with Six SolarWorld SW 280 Mono Panels](image)

### 4.5 Connecting the Wires and Electric Vehicle Charger

Once the concrete had set, the plywood template on top of the filled hole was removed. This meant that in theory, the pedestal could be installed. However, the J bolts shifted after installation so they did not match up with the pedestal slots. Furthermore, the PVC pipe coming out of the concrete was at an angle, so the pedestal could not even sit flat on the ground. To fix the problems, the appropriate spots were marked on the pedestal and Tom Cochrane cut it with a plasma cutter. Kenny McNeal heated the PVC and bent it to the appropriate shape to fit in the pedestal. In order to run all of the necessary copper wire through the 100 ft of PVC pipe underneath the ground, a strong rope was inserted and a vacuum was used to suck it through to the other side. The copper was then attached to the rope. Figure 50 shows the forklift pulling the wire through the PVC pipe while it was fed into the other end.
an embodied carbon of 2193 kg, this will be made up in just 7.6 months when counting
the transportation savings from incentivizing EV adoption. Even without counting
the daily Swarthmore commute, the payback will be 5.5 years.

From an economic point of view, Swarthmore is not able to take advantage of
many of the incentives in Pennsylvania due to its non-profit status. The analysis was
therefore carried out as if this was a residential system. Assuming a 25 year lifetime,
a 30% ITC and the Federal MACRS incentives, and several other factors, the initial
cost of $8,800 would be paid back in 12 years. Therefore, the net present value with
a 5% discount rate is $1,202. The LCOE of this system is only 5.52 cents per kWh,
which is much less than the average retail cost of electricity at 14.62 cents per kWh.

As of the time of writing, real time output from the solar panels can be found at

6.1 Look-back Improvements

Looking back, there are several areas where we would have done things differently. As
far as the construction is concerned, the top restraining two by four on the framework
could have been installed in advance, as the side plywood panels were not completely
flat. Furthermore, after seeing how easy it was to move the beams using the forklift,
they could have been cast in a location further away from the site that was still flat.
The concrete sunk slightly to one corner on each ballast due to this. We could also
have paid more attention to the finishing aspects of the concrete, although this was
outside of the project scope as the ballasts are only noticeable when very close to the
structure.

In hindsight, it would also have been good to double check the plywood template
for the EV charger base against the base itself to ensure the J-bolts in the concrete
matched up before the concrete had set. The angle of the PVC pipe could also have
been considered in advance. The overall choice of which electric vehicle charger to
purchase would be rethought, as there were several installation problems and some
small design issues that make its stated endurance slightly questionable.

6.2 Future Improvements

There are many interesting problems associated with our project that were outside
of project scope. Listed below are areas of future improvement and research:

- Tracking annual solar output and EV usage
Moving on from the electric vehicle charger, it was necessary to ground the PvMini. In order to do this, several ground lugs were installed on each of the three struts. These ground lugs were then attached to a large grounding rod that had been driven 6 ft into the ground. While 10 gauge wire was used initially, it will be replaced with even thicker solid wire so that it can handle a lightning strike.

The solar panels connect to the Enphase microinverters using a clip, and the connections have O-rings on them to ensure they are waterproof. The microinverter cable was tied off with an endcap at one end, and the other end was run into the box in Figure 53 where it was hooked up to the cable that had been pulled through the PVC pipe. The box was attached to unistrut using spring nuts.

![External Box for Inverter Connections](image)

At the house end of the PVC pipe, the wire was run through a disconnect and a revenue grade meter. These two are in Figures 54 and 55. From the disconnect, the wires were run into the house, where they were hooked up to a sub breaker panel. From this point they were able to feed back into the grid. The revenue grade meter is for tax credit purposes, as the Enphase meter is only for providing live feedback on the Enphase Enlighten website.
4.6 Installing Metering Equipment

The Enphase M250 microinverters pair well with the Enphase Envoy Communications Gateway to provide nearly live data on the production of each solar panel through the Enphase Enlighten website. It uses powerline connections to collect the data from the neutral wires from the microinverters. Therefore, it was necessary to attach it to an outlet connected to the same circuit breaker. Once hooked in and turned on, the device was able to see all six panels, as seen in Figure 56. In order to communicate with the Enlighten website, the device had to be hooked up to the Ethernet. Luckily, there was an Ethernet switch only a few feet away which it was possible to plug into. The device is now communicating, and as of writing it is possible to access the data through https://enlighten.enphaseenergy.com/pv/public_systems/h5Xt625914.
5 Estimating Project Impact

To properly assess whether the project would be beneficial or not, we estimated the project impact in terms of its effects on greenhouse gas emissions and its economic returns. In particular, we were interested in the carbon payback and economic payback of the system.

5.1 Impact on Greenhouse Gas (GHG) Emissions

To understand our project’s impact on GHG emissions, we needed to calculate the carbon embodied in the various components of the project and estimate future avoided carbon emissions. The latter relies on estimates of PV production and EV usage outlined earlier in this report. A full audit of GHG impact would require tracking actual PV output and EV usage, which is an area of future work.

5.1.1 System Embodied Carbon

The embodied carbon was only considered for the photovoltaic-related components of the system, as it would have been almost impossible to consider the embodied carbon
of the electric vehicle charger without a better understanding of the internal systems. The Inventory of Carbon and Energy database was used in order to determine the kg of CO₂ per kg of material. Each material had its own methodology to find the embodied carbon, although the results are summarized in Table 3.

Starting with concrete, the embodied carbon of concrete is \( \frac{0.159 \text{ kg CO}_2}{\text{kg concrete}} \) \[16\]. In the project, about 1.5 cubic yards of concrete were used, which translates to 6075 lbs of concrete assuming 150 \( \text{lbs/ft}^3 \). Converting this to kg gives 2756 kg of concrete. Therefore, the embodied carbon is

\[
(2756 \text{ kg Concrete}) \left( \frac{0.159 \text{ kg CO}_2}{\text{kg concrete}} \right) = 438 \text{ kg CO}_2.
\]

Continuing with the rebar, the embodied carbon of rebar is \( \frac{1.37 \text{ kg CO}_2}{\text{kg steel}} \) assuming it is steel with an average recycling content \[16\]. To find the total mass, 12 pieces of #4 rebar were used that were all 60 in long. This translates to a length of 18.29 m. Standard #4 rebar is 0.996 \( \text{kg/m} \), so the total mass is 18.22 kg. This leads to an embodied carbon of

\[
(18.22 \text{ kg rebar}) \left( \frac{1.37 \text{ kg CO}_2}{\text{kg steel}} \right) = 25.0 \text{ kg CO}_2.
\]

Moving onto the aluminum, the embodied carbon of aluminum is \( \frac{8.24 \text{ kg CO}_2}{\text{kg aluminum}} \) \[16\]. The struts were assumed to be made of 1 in square tubing, which has a standard weight of 0.02283 \( \text{lb/ft} \). Adding up all of the tubing in the structure gives a total length of 233.1 in. This leads to a total weight of 2.414 kg of aluminum for just the strut structures. The perlins were assumed to weigh about 10 lbs, which is 4.536 kg. Therefore the embodied carbon of the aluminum is

\[
((2.414 + 2 \times 4.536) \text{ kg aluminum}) \left( \frac{8.24 \text{ kg CO}_2}{\text{kg aluminum}} \right) = 94.6 \text{ kg CO}_2.
\]

Finally, solar panels emit \( 30 \text{ g CO}_2 / \text{kWh} \) when doing a full lifecycle analysis \[13\]. From the SAM model, the expected lifetime generation is 54.5 MWh. Therefore the embodied carbon is

\[
(54.5 \times 10^2 \text{ kWh}) \left( \frac{0.03 \text{ kg CO}_2}{\text{kWh}} \right) = 1635 \text{ kg CO}_2.
\]
Table 3: Embodied Carbon Totals

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
<th>Unit Embodied Carbon</th>
<th>Embodied Carbon (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>2760 kg</td>
<td>0.159 kg CO₂/kg</td>
<td>438</td>
</tr>
<tr>
<td>Rebar</td>
<td>18.21 kg</td>
<td>1.37 kg CO₂/kg</td>
<td>25.0</td>
</tr>
<tr>
<td>Aluminum</td>
<td>21.9 kg</td>
<td>8.24 kg CO₂/kg</td>
<td>94.64</td>
</tr>
<tr>
<td>Solar Panels</td>
<td>54.5 MWh</td>
<td>0.03 g CO₂/kWh</td>
<td>1635</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>2193</strong></td>
</tr>
</tbody>
</table>

5.1.2 Avoided GHG Emissions

This project will avoid GHG emissions through PV production and enabling EV adoption. The lifetime PV production will offset energy that otherwise would have been drawn from the electrical grid. The avoided GHG emissions can be obtained by multiplying lifetime production by the carbon intensity of energy supply in Pennsylvania, which was $1.89 \times 10^{-4}$ MT CO₂ / kWh in 2011 according to the U.S. EIA [3]. The second can be considered an avoided GHG under the perception that installing EV charging stations will increase EV adoption and fuel-switching. This seems plausible since range anxiety and lack of support infrastructure are often cited reasons for slow rates of EV adoption [12] [19]. Since the idea of our project is to offset EV usage with solar output, we can come up with the best-case scenario for our system: that all the energy produced goes into powering EVs. If that is the case, then we can multiply the annual mileage offset by our solar power by the average carbon intensity of passenger transportation in the country, which was $4.20 \times 10^{-4}$ MT CO₂ / mile [4]. If EV energy usage is less than PV generation, then our method would overestimate avoided emissions in the transportation sector. On the other hand, if EV energy usage exceed PV generation, there would be additional avoided emissions since the carbon intensity of energy supply times (MT CO₂ / kWh) times electric vehicle efficiency (kWh / mile) is $5.88 \times 10^{-5}$ MT CO₂ / mile, which is 1/7 of the average carbon intensity of passenger transportation using internal combustion vehicles. Thus, with the annual energy output modeled in the SAM 3-D shading model, our system will achieve the GHG emissions outlined in Table 4.
### Table 4: Project Avoided Emissions

<table>
<thead>
<tr>
<th>Avoided GHG by Sector</th>
<th>Annual (MT CO2)</th>
<th>Net Lifetime (MT CO2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0.42</td>
<td>7.69</td>
</tr>
<tr>
<td>Transportation</td>
<td>2.99</td>
<td>68.4</td>
</tr>
<tr>
<td>Total</td>
<td>3.41</td>
<td>78.2</td>
</tr>
<tr>
<td>% of 2013 Emissions</td>
<td>0.02</td>
<td></td>
</tr>
</tbody>
</table>

The system has an embodied carbon payback 7.6 months if you count both electricity and transportation sector impacts, and 5.5 years with only the electricity sector. Regardless, the system is expected to reduce 78.2 metric tons (MT) of CO₂, net of the carbon that went into building it.

### 5.2 Economic Impact

To estimate the economic performance of our project, we modeled the system as a behind-the-meter solar system on PECOs residential tariff with net energy metering (NEM). We chose to do this because this enables the system to capture more solar incentives than a college-owned system, as the majority of solar incentives are only available for tax-paying entities. We chose the residential tariff because the College’s electric rate is much lower than the rate that most residences pay, and would thus extend the payback of a solar system. This analysis represents an optimistic estimate of project economics.

#### 5.2.1 Solar Incentives and Credits

The two major solar incentives available today are the 30% federal solar investment tax credit (ITC), and the Modified Accelerated Cost Reduction System (MACRS) depreciation for solar assets.

The ITC is a 30 percent federal tax credit for solar systems on residential and commercial properties that remains in effect through December 31, 2016 (when it will be adjusted to 10%). The commercial ITC is used for utility-scale, commercial and residential sized projects; the company that installs, develops or finances the project uses the credit. The residential ITC is used for residential sized projects, and the homeowner applies the credit to his/her income taxes. This credit is used when homeowners purchase solar systems outright and have them installed on their homes.

Under the federal Modified Accelerated Cost-Recovery System (MACRS), businesses may recover investments in certain property through depreciation deductions.
A number of renewable energy technologies are classified as five-year property including a variety of solar electric and solar thermal technologies. This allows for the deduction of 100% of the solar panels cost from taxable income over a five year period, resulting in an incentive of approximately 35% of the system cost.

In addition to the ITC and MACRS, solar PV output is eligible to be sold as solar renewable energy credits (SRECs) on the Pennsylvania SREC market. PA is one of the two remaining PJM SREC markets allows systems to register from out of state (other being Ohio), so as a result, the market has been oversupplied for the past few years, resulting in relatively low SREC prices ($30-60 / MWh). Otherwise, there no other state incentives or tax exemptions for solar in PA.

5.2.2 Project Economics

Applying the following parameters, we were able to model the economics of the solar output over the lifetime of the system:

- 25 year lifetime
- 30% ITC and Federal MACRS
- SREC value of $0.06 / kWh
- 5% discount rate
- No debt
- Maintenance costs of $20/kW per year
- Electric rate of 14.62 cents / kWh and net energy metering
- Rate escalation of 0.5% per year (2015 AEO reference case)

The cumulative cash flows, along with economic payback, are shown in Figure 57.
With an initial cost of $8,800, the project will payback in economic terms in around 12 years. This results in a net present value of $1,202. Over 25 years, the electricity cost without the solar PV (cost of charging EVs) is $391; with the system, the cost is $67. This results in a levelized cost of energy of 5.52 cents per kWh. This is much lower than the cost of retail electricity (14.62 cents per kWh), even after netting the transmission and distribution costs. This suggests that overall, the solar PV system is cost-effective from an economic perspective.

Note: to calculate total project payback, we used the total cost of materials for the project. This does not include materials that were readily available or the labor that went into the project. For levelized cost of energy calculation (LCOE), the cost of EV charging equipment was not considered since it is not needed for generating energy. LCOE is an economic assessment of the average total cost to build and operate a power-generating asset over its lifetime divided by the total power output of the asset over that lifetime.

6 Conclusion

Overall, this project was mostly successful in achieving the initial goals despite the move away from the solar carport. A ground mounted array of six solar panels was constructed within in the same sightline as an electric vehicle charger which can power two electric vehicles simultaneously at level 2 charging. A rudimentary Revit model was created of a full size carport and rendered to provide an idea of what a full parking lot system would look like.

The lifetime production of the PV array is 54.5 MWh. The projected avoided emissions over the design life of the project is 78.2 metric tons of CO₂. Despite having
an embodied carbon of 2193 kg, this will be made up in just 7.6 months when counting
the transportation savings from incentivizing EV adoption. Even without counting
the daily Swarthmore commute, the payback will be 5.5 years.

From an economic point of view, Swarthmore is not able to take advantage of
many of the incentives in Pennsylvania due to its non-profit status. The analysis was
therefore carried out as if this was a residential system. Assuming a 25 year lifetime,
a 30% ITC and the Federal MACRS incentives, and several other factors, the initial
cost of $8,800 would be paid back in 12 years. Therefore, the net present value with
a 5% discount rate is $1,202. The LCOE of this system is only 5.52 cents per kWh,
which is much less than the average retail cost of electricity at 14.62 cents per kWh.

As of the time of writing, real time output from the solar panels can be found at

6.1 Look-back Improvements
Looking back, there are several areas where we would have done things differently. As
far as the construction is concerned, the top restraining two by four on the framework
could have been installed in advance, as the side plywood panels were not completely
flat. Furthermore, after seeing how easy it was to move the beams using the forklift,
they could have been cast in a location further away from the site that was still flat.
The concrete sunk slightly to one corner on each ballast due to this. We could also
have paid more attention to the finishing aspects of the concrete, although this was
outside of the project scope as the ballasts are only noticeable when very close to the
structure.

In hindsight, it would also have been good to double check the plywood template
for the EV charger base against the base itself to ensure the J-bolts in the concrete
matched up before the concrete had set. The angle of the PVC pipe could also have
been considered in advance. The overall choice of which electric vehicle charger to
purchase would be rethought, as there were several installation problems and some
small design issues that make its stated endurance slightly questionable.

6.2 Future Improvements
There are many interesting problems associated with our project that were outside
of project scope. Listed below are areas of future improvement and research:

- Tracking annual solar output and EV usage
- Optimize positioning of modules on PVMini to reduce new shading from tree growth
- Implementing a single or dual axis tracking system for the solar array
- Creating an authentication system for EV charging
- Designing a scheduling system to coordinate use of the EV charging equipment
References


import numpy as np

# Erik Jensen
# E90 May 2015
# Swarthmore College

# Chose to do Elastic Analysis, as the structure is intended
# never to have any permanent deformation for aesthetic
# purposes

def flexureTest(Sx, M, f_y=60):
    # For units, assumes
    # M: kip-ft
    # Sx: in^3
    
    # Calculating ultimate moment of beam
    M_ult = f_y*Sx

    # Checking the moment after converting to in
    if M*12 <= M_ult:
        return True
    else:
        return False

def shearTest(V, tw, d, tf, E=30000, f_y=60):
    # Performs a shear test of the given loading situation,
    # assuming the modulus of elasticity is 30,000 ksi as
    # it would be for steel.
    # Area of web
h = d-tf
A_w = h*tw

# Checking for web instability and then finding ultimate shear
a = h/tw
b = 2.45*np.sqrt(E/f_y)
c = 3.07*np.sqrt(E/f_y)

if a <= b:
    Vn = 0.6*f_y*A_w
elif b < a and a < c:
    Vn = 0.6*f_y*A_w*(2.45*np.sqrt(E/f_y)/(h/tw))
elif c < a and a < 260:
    Vn = A_w*(4.52*E/((h/tw)**2))

# Finally checking the shear capacity
if V <= Vn:
    return True
else:
    return False

def ltbTest(bf, tf, d, tw, r_y, A, Sx, J, cw, ly, L_b, isC, M, E=29000, f_y=60, G=11200):
    # Performs the lateral torsional buckling test for compact sections.
    # Given that only sections from tables were used, it is only necessary
    # to consider compact sections, as all hotrolled sections have webs th
    # meet the criteria while the flange almost always meets criteria.
    # First checking to see if flange and web are compact,
    # noncompact, or slender
    # First the flange
    if isC == 0:
        lambdaFRatio = bf / (2*tf)
    else:
        lambdaFRatio = bf/tf
\[ \lambda_{F_p} = 0.38 \times \sqrt{\frac{E}{f_y}} \]
\[ \lambda_{F_r} = 0.83 \times \sqrt{\frac{E}{f_y - 10}} \]

# New the web
\[ \lambda_{W_{\text{Ratio}}} = \frac{d - tf}{tw} \]
\[ \lambda_{W_p} = 3.76 \times \sqrt{\frac{E}{f_y}} \]
\[ \lambda_{W_r} = 5.70 \times \sqrt{\frac{E}{f_y}} \]

# Calculating important section properties
\[ L_p = 1.76 \times r_y \times \sqrt{\frac{E}{f_y}} \]
\[ f_r = 10 \quad \# \text{ksi, rolled shape, compressive residual stress} \]
\[ f_L = f_y - f_r \]
\[ X_1 = \left( \frac{\pi}{S_x} \right) \times \sqrt{\frac{E \times G \times J \times A}{2}} \]
\[ X_2 = \left( \frac{4 \times cw}{ly} \right) \times \left( \frac{S_x}{(G \times J)} \right)^2 \]
\[ L_r = \left( r_y \times X_1 / f_L \right) \times \sqrt{1 + \frac{1}{X_2} \left( \frac{1}{LL} \right)^2} \]
\[ M_r = f_L \times S_x \]

# Assume a conservative design, considers non-uniform bending moment distribution
\[ C_b = 1 \]

# Checking to see if compact and then performing test
if \( \lambda_{F_{\text{Ratio}}} \leq \lambda_{F_p} \) and \( \lambda_{W\text{Ratio}} \leq \lambda_{W_p} \):
    print 'The section is compact...'
    \[ M_{\text{ult}} = f_y \times S_x \]
else:
    if \( L_p \leq L_b \) and \( L_b \leq L_r \):
        \[ M_n = C_b \times (M_{\text{ult}} - (M_{\text{ult}} - M_r) \times \frac{(L_b - L_p)}{(L_r - L_p)}) \]
    else:
        \[ M_{cr} = C_b \times (\sqrt{\frac{E \times I_y \times G \times J}{\pi L_b}} + \frac{(\pi \times E \times L_b)^2}{I_y \times cw}) \]
        if \( M_{cr} \leq M_{\text{ult}} \):
            \[ M_n = M_{cr} \]
        else:
            \[ M_n = M_{\text{ult}} \]
elif (lambdaF_ratio > lambdaFRatio) or (lambdaW_ratio > lambdaWratio):
    # slender
    print 'The section is noncompact. Try again :('
    return False
else:  # noncompact
    print 'The section is slender. Try again :('
    return False

if M <= M_n:
    return True
else:
    return False

# define Beam(n):
# Allows you to select which beam to test. 0 is the channel
# section.

if n == 0:
    A = 2.4  # in^2
    d = 6   # in
    bf = 1.92  # in
    tf = 0.343  # in
    tw = 0.2   # in
    Ix = 13.1  # in^4
    Iy = 0.693  # in^4
    Sx = 4.35   # in^3
    h = 0  # in, not considered for channel
    ry = 0.536  # in
    J = 0.0736  # in^4
    cw = 4.7  # in^6, warping constant
    L = 78   # in, unbraced length of beam
    isC = 1  # If a channel section, = 1, else, =0

    return A, d, bf, tf, tw, Ix, Iy, Sx, h, ry, J, cw, L, isC
def testBeam():
    # Select which beam to use
    bSelect = 0

    # The properties of the beam
    Area, d, bf, tf, tw, Ix, Iy, Sx, h, r_y, J, cw, L, isC = defineBeam(bSelect)

    # Performing the different tests
    A = np.zeros(3)
    M = 0
    V = 0
    A[0] = flexureTest(Sx, M)
    A[1] = shearTest(V, tw, d, tf)
    A[2] = ltbTest(bf, tf, d, tw, r_y, Area, Sx, J, cw, Iy, L, isC, M)
    if np.all(A):
        print 'It works!'
B Initial AutoCAD/Revit Designs
**Report Name**: Southern  
**Report Date**: 4/1/2015 8:40:11 PM  
**Declination**: -12d 03m  
**Location**: Swarthmore, PA 19081  
**Lat/Long**: 38.897/-75.344  
**Weather Station**: Philadelphia Intl AP, PA, Elevation: 7 Feet, (39.867/-75.233)  
**Site Distance**: 6 Miles  
**Report Type**: PV  
**Array Type**: Fixed Angle  
**Tilt Angle**: 39.90 deg  
**Ideal Tilt Angle**: 39.90 deg  
**Azimuth**: 180.00 deg  
**Ideal Azimuth**: 180.00 deg  
**Electric Cost**: 0.12 ($/KWH)  
**Panel Make**: <not specified>  
**Panel Model**: <not specified>  
**Panel Count**: 1  
**DC Rate (per panel)**: 280.0 Watts  
**Total System Size**: 280.0 Watts  
**Inverter Make**: <not specified>  
**Inverter Model**: <not specified>  
**Inverter Count**: 1  
**Derate Method**: Inverter Derate Only  
**Derate Factor**: 0.985  
**Layout Configuration**: Custom  
**Layout Point Count**: 2

**Notes**: [None]
Swarthmore College Engineering Dept
System Picture Layout

Layout Type: Custom
Layout Point Count: 2

Panel/Array
### Solar Obstruction Data (Part 1 of 2)

<table>
<thead>
<tr>
<th>Month</th>
<th>Actual Shaded Solar Radiation Azimuth=180.0 Tilt=39.9 KWhr/m² 2</th>
<th>Actual Shaded AC Energy (KWH) Azimuth=180.0 Tilt=39.9</th>
<th>Actual Unshaded AC Energy (KWH) Azimuth=180.0 Tilt=39.9</th>
<th>Ideal Unshaded AC Energy (KWH) Azimuth=180.0 Tilt=39.9</th>
<th>PV Solar Cost Savings 0.12 ($) KWH</th>
<th>PV Watts Unshaded % Actual Site Azimuth=180.0 Tilt=39.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>2.70 24.52 32.00 32.00</td>
<td>$2.94 76.79 %</td>
<td>$2.96 77.98 %</td>
<td>$3.46 73.80 %</td>
<td>$3.15 68.05 %</td>
<td>$3.55 68.11 %</td>
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<tr>
<td>February</td>
<td>3.15 24.47 31.00 31.00</td>
<td>$2.98 77.98 %</td>
<td>$3.38 67.98 %</td>
<td>$3.39 67.98 %</td>
<td>$3.40 67.95 %</td>
<td>$3.25 73.12 %</td>
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<tr>
<td>March</td>
<td>3.49 28.66 39.00 39.00</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.38 67.95 %</td>
<td>$3.25 73.12 %</td>
</tr>
<tr>
<td>April</td>
<td>3.47 29.23 36.00 36.00</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.38 67.95 %</td>
<td>$3.25 73.12 %</td>
</tr>
<tr>
<td>May</td>
<td>3.69 29.64 42.00 42.00</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.38 67.95 %</td>
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</tr>
<tr>
<td>June</td>
<td>3.97 28.19 40.00 40.00</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.38 67.95 %</td>
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<tr>
<td>July</td>
<td>3.69 29.64 42.00 42.00</td>
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<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.38 67.95 %</td>
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</tr>
<tr>
<td>August</td>
<td>3.91 28.33 41.00 41.00</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
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<td>September</td>
<td>3.76 27.13 36.00 36.00</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.38 67.95 %</td>
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<td>October</td>
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<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.38 67.95 %</td>
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<tr>
<td>November</td>
<td>2.78 23.12 30.00 30.00</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
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<tr>
<td>December</td>
<td>2.55 21.62 28.00 28.00</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.46 73.80 %</td>
<td>$3.38 67.95 %</td>
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<tr>
<td>Totals</td>
<td>44.76 317.34 431.00 431.00</td>
<td>$38.08 73.30 %</td>
<td>$38.08 73.30 %</td>
<td>$38.08 73.30 %</td>
<td>$38.08 73.30 %</td>
<td>$38.08 73.30 %</td>
</tr>
</tbody>
</table>

**Effect:** 72.50%

**Unweighted Yearly Avg**

### Notes:
- [None]
## D.1 3-D Shading SAM Output Case

### Performance Model

<table>
<thead>
<tr>
<th>Component</th>
<th>Details</th>
</tr>
</thead>
<tbody>
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<td>Modules</td>
<td>Mono-crystalline 280 mono</td>
</tr>
<tr>
<td>Cell material</td>
<td>Monocrystalline</td>
</tr>
<tr>
<td>Module area</td>
<td>1.7 m²</td>
</tr>
<tr>
<td>Module capacity</td>
<td>265 DC Watts</td>
</tr>
<tr>
<td>Quantity</td>
<td>6</td>
</tr>
<tr>
<td>Total capacity</td>
<td>1.7 kW</td>
</tr>
<tr>
<td>Total area</td>
<td>19 m²</td>
</tr>
<tr>
<td>Inverter</td>
<td>Enphase Energy: M260-60-2L-S2 (ZC) (240)</td>
</tr>
<tr>
<td>Unit capacity</td>
<td>240 DC Watts</td>
</tr>
<tr>
<td>Input voltage</td>
<td>27 - 39 VDC</td>
</tr>
<tr>
<td>Quantity</td>
<td>6</td>
</tr>
<tr>
<td>Total capacity</td>
<td>1.4 AC MW</td>
</tr>
<tr>
<td>DC to AC Capacity Ratio</td>
<td>0.00</td>
</tr>
<tr>
<td>AC loss ratio</td>
<td>1.0</td>
</tr>
<tr>
<td>Array</td>
<td>6</td>
</tr>
<tr>
<td>Module per string</td>
<td>1</td>
</tr>
<tr>
<td>String voltage (DCV)</td>
<td>112.0</td>
</tr>
<tr>
<td>Tilt (deg from horizontal)</td>
<td>38</td>
</tr>
<tr>
<td>Azimuth (deg E of N)</td>
<td>190</td>
</tr>
<tr>
<td>Tracking</td>
<td>fixed</td>
</tr>
<tr>
<td>Power limit (deg)</td>
<td>142</td>
</tr>
<tr>
<td>Shading</td>
<td>yes</td>
</tr>
<tr>
<td>Soiling</td>
<td>yes</td>
</tr>
<tr>
<td>DC loss ratio (%)</td>
<td>2.5</td>
</tr>
</tbody>
</table>

### Financial Model

<table>
<thead>
<tr>
<th>Model</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total installed cost</td>
<td>$6,466</td>
</tr>
<tr>
<td>Salvage value</td>
<td>$1,614</td>
</tr>
<tr>
<td>Project life</td>
<td>26 years</td>
</tr>
<tr>
<td>Inflation rate</td>
<td>2%</td>
</tr>
<tr>
<td>Real discount rate</td>
<td>2.5%</td>
</tr>
<tr>
<td>Debt fraction</td>
<td>0%</td>
</tr>
<tr>
<td>Amount</td>
<td>$0</td>
</tr>
<tr>
<td>Term</td>
<td>25 years</td>
</tr>
<tr>
<td>Rate</td>
<td>5%</td>
</tr>
<tr>
<td>Tax and insurance Rates (%)</td>
<td>1.87%</td>
</tr>
<tr>
<td>Federal income tax</td>
<td>30%</td>
</tr>
<tr>
<td>State income tax</td>
<td>2.07%</td>
</tr>
<tr>
<td>Sales tax</td>
<td>0%</td>
</tr>
<tr>
<td>Insurance</td>
<td>0%</td>
</tr>
<tr>
<td>Property tax (%)</td>
<td>1.87%</td>
</tr>
<tr>
<td>Federal ITC</td>
<td>30%</td>
</tr>
<tr>
<td>Federal Depreciation</td>
<td>5%</td>
</tr>
<tr>
<td>State Depreciation</td>
<td>5%</td>
</tr>
<tr>
<td>State PBD</td>
<td>6 cents/kWh; 30 yrs</td>
</tr>
</tbody>
</table>

### Electricity Demand and Rate Summary

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual peak demand -1.6 kW</td>
<td>10.0 kW</td>
</tr>
<tr>
<td>Annual total demand -1.9 kW</td>
<td>14.0 kW</td>
</tr>
<tr>
<td>PECO Energy Co</td>
<td>$9.97/month</td>
</tr>
<tr>
<td>Flat rate (kW)</td>
<td>$0.14/kWh</td>
</tr>
</tbody>
</table>

### Performance Adjustments

- **Annual:** no
- **Year-to-year decline:** 0.5
- **Hourly factor:** yes

### Annual Results (in Year 1)

- GHI kWh/m²/day: 4.0
- POA kWh/m²/yr: 3.0
- DC kWh from array: 2.300
- DC kWh from inverter: 2.300
- DC kW from inverter: 2.300
- DC kW to grid: 2.200
- Capacity factor: 14.91
- Performance ratio: 0.9
Photovoltaic System
Commercial
1.70 kW Nameplate
$3.80 kW-NAMEPLATE-Installed Cost
Philadelphia International Ap, PA
39.87 N, -75.23 E GMT -5

Electricity from System (kWh)

Electricity to Load (kWh)

Electricity to (from) Grid (kWh)

Net Metering Credits (kWh)

<table>
<thead>
<tr>
<th>Month</th>
<th>Without System</th>
<th>With System</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>33</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Feb</td>
<td>30</td>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td>Mar</td>
<td>31</td>
<td>8</td>
<td>22</td>
</tr>
<tr>
<td>Apr</td>
<td>32</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>May</td>
<td>32</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Jun</td>
<td>31</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>Jul</td>
<td>33</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>Aug</td>
<td>31</td>
<td>8</td>
<td>22</td>
</tr>
<tr>
<td>Sep</td>
<td>32</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Oct</td>
<td>33</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>Nov</td>
<td>30</td>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td>Dec</td>
<td>33</td>
<td>-32</td>
<td>66</td>
</tr>
<tr>
<td>Annual</td>
<td>391</td>
<td>67</td>
<td>324</td>
</tr>
</tbody>
</table>

NPV Approximation using Annuities

Annuities, Capital Recovery Factor (CRF) = 0.0678
Investment = Installed Cost - Debt Principal + IBI - CBI
Expenses = Operating Costs - Debt Payments
Savings = Tax Deductions + PBI
Energy value = Tax Adjusted Net Savings
Nominal discount rate = 45.5%

Payback Cash Flow (Payback Period = 8.4 years)
# D.2 Pathfinder Shading SAM Output Case

## System Advisor Model Report

**Photovoltaic System**: 1.70 kW Nameplate  
**Commercial**  
**$3.80/W Installed Cost**:  
**Philadelphia International Ap, PA**:  
**39.87 N, -75.23 E GMT-5**

## Performance Model

<table>
<thead>
<tr>
<th>Modules</th>
<th>Financial Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modules</strong></td>
<td><strong>Project Costs</strong></td>
</tr>
<tr>
<td>Solar World SW 380 mono</td>
<td>Total installed cost $6,456</td>
</tr>
<tr>
<td>Cell material</td>
<td>Salvage value $1,614</td>
</tr>
<tr>
<td><strong>Modules</strong></td>
<td><strong>Analytical Parameters</strong></td>
</tr>
<tr>
<td>Mono-crystalline</td>
<td>Project life 36 years</td>
</tr>
<tr>
<td><strong>Modules</strong></td>
<td><strong>Project Debt Parameters</strong></td>
</tr>
<tr>
<td>** Modules**</td>
<td><strong>Tax and Insurance Rates</strong></td>
</tr>
<tr>
<td></td>
<td>Debt @ Project life 0%</td>
</tr>
<tr>
<td></td>
<td>Amount $0</td>
</tr>
<tr>
<td></td>
<td>Term 0 years</td>
</tr>
<tr>
<td></td>
<td>Rate 5%</td>
</tr>
<tr>
<td></td>
<td>Federal income tax 30%/year</td>
</tr>
<tr>
<td></td>
<td>State income tax 2.07%/year</td>
</tr>
<tr>
<td></td>
<td>Sales tax 0%</td>
</tr>
<tr>
<td></td>
<td>Insurance 0%/year</td>
</tr>
<tr>
<td></td>
<td>Property tax (1% of assessed value) 1.87%/year</td>
</tr>
</tbody>
</table>

## Financial Model

### Incentives

- Federal ITC 30%
- Federal Depreciation 5-year MACRS
- State Depreciation 5-year MACRS
- State PBI 6 months; 30 year

## Electricity Demand and Rate Summary

- Annual peak demand: 1.6 kW
- Annual total demand: 1.862 kW
- PECO Energy Co.
- Fixed fee: $9.07/month
- Flat rate (kWh) $0.140/kWh

## Financial Model

### Data

- Nameplate power 1.7 kW
- Installed cost $3.80/kW
- Sales tax 6%
- Total cost $6,456
- Salvage value $1,614
- Project life 36 years
- Federal income tax 30%
- State income tax 2.07%
- Sales tax 0%
- Insurance 0%
- Property tax (1% of assessed value) 1.87%

## Array

- Modules per string 1
- String voltage (DC-V) 31.2
- Shading yes
- DC loss (%) 2.5

## Performance Adjustment

- Annual 0%
- Year-to-year decline 0.6%
- Hourly factor:
  - on-grid 1.0270 A-1h
  - off-grid 1.0270 A-1h
- Performance ratio 0.9

## Commercial PV System Efficiency Model

*System Advisor Model Standard Report generated by SAM 2015.1.30 on Fri May 15 00:53:59 2015*
Photovoltaic System: 1.70 kW Nameplate $3.80/W Installed Cost
Commercial
Philadelphia International Ap, PA 39.87 N, -75.23 E GMT -5

Electricity from System (kWh)

Electricity to Load (kWh)

Electricity to (from) Grid (kWh)

Net Metering Credits (kWh)

Monthly Electricity Purchases and Savings (Year 1 $)

<table>
<thead>
<tr>
<th>Month</th>
<th>Without System</th>
<th>With System</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>33</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>Feb</td>
<td>30</td>
<td>11</td>
<td>19</td>
</tr>
<tr>
<td>Mar</td>
<td>33</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Apr</td>
<td>33</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>May</td>
<td>31</td>
<td>8</td>
<td>23</td>
</tr>
<tr>
<td>Jun</td>
<td>33</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Jul</td>
<td>34</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>Aug</td>
<td>31</td>
<td>8</td>
<td>26</td>
</tr>
<tr>
<td>Sep</td>
<td>33</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Oct</td>
<td>33</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Nov</td>
<td>31</td>
<td>8</td>
<td>23</td>
</tr>
<tr>
<td>Dec</td>
<td>34</td>
<td>9</td>
<td>34</td>
</tr>
<tr>
<td>Annual</td>
<td>395</td>
<td>104</td>
<td>289</td>
</tr>
</tbody>
</table>

NPV Approximation using Annuities

<table>
<thead>
<tr>
<th>Annuities, Capital Recovery Factor (CRF) = 0.0678</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment $-400</td>
</tr>
<tr>
<td>Expenses $-400</td>
</tr>
<tr>
<td>Savings $0</td>
</tr>
<tr>
<td>Energy value $-5,000</td>
</tr>
</tbody>
</table>

Investment = Installed Cost - Debt Principal - IBI - CBI
Expenses = Operating Costs + Debt Payments
Savings = Tax Deductions + PBI
Energy value = Tax Adjusted Net Savings
Nominal discount rate = 4.55%

Payback Cash Flow (Payback Period = 9.2 years)
Nominal POA (kWh)
17,193

Nominal DC energy (kWh)
2,205
- Shading -19.09%
- Soiling -4.99%

Net DC energy (kWh)
2,085
- Module loss -0.014%
- Connections -0%
- Mismatch -0.497%
- DC wiring -1.591%
- Tracking -0%
- Nameplate -0%

Gross AC energy (kWh)
1,998
- Ac wiring -1.017%
- Inverter clipping -2.151%
- Inverter power -0.999%
- Inverter efficiency -1.721%
- Inverter output tracking -0%
- Inverter efficiency -1.721%

Net AC energy (kWh)
1,978
- Step-up transformer -0%
- Performance adjustment -0%

Annual energy (kWh)
1,978

System Advisor Model Standard Report generated by SAM 2016.1.30 on Fri May 06 00:00:50 2016