

Solar Photovoltaic Shade Canopy Feasibility

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Abstract

A significant challenge in urban living, especially low income neighborhoods, is the lack of canopy cover to provide shade for communities during the hot summer months. Solar Canopies are canopy structures that both provide shade and have solar panels on top to produce electricity. They have been growing in popularity, most notably for parking lot cover. This project aims to address the lack of shade in urban areas using solar canopy structures over basketball courts. Using basketball courts, rather than parking lots, draws community members to a recreational outdoor space that may be utilized when it was otherwise inaccessible due to the sun and heat. Moreover, the electricity generated from the canopy can provide economic benefit to the community. This project looks specifically at the implementation of a solar canopy structure in two locations, Hialeah Miami Lakes Senior High School in Miami Florida, and Madison Highland Prep Middle School in Phoenix. From a solar resource and economic analysis, it is discovered that a structure covering two basketball courts can be built in the Miami location that produces about 227.5 MWh of electricity, has a capacity factor of about 17%, and costs about \$543,000 to build. A structure covering only one basketball court can be built in the Phoenix location producing about 151MWh with a capacity factor of 18.7%, totaling about \$541,000. The LCOE of the Miami and Phoenix structures are \$0.166/kWh and \$0.155/kWh respectively when not including the cost of the canopy and \$0.285/kWh and \$0.261/kWh respectively when including the cost of the structure.

Introduction

Motivation

The goal of this project is to analyze the feasibility of installing solar photovoltaic shade canopies in a disadvantaged community public space. This would provide shade and improve the space conditions for the people using it during the hot months, as well as increase the amount of energy coming from sunlight. In addition, the overflow amount of energy could be sold to the central power grid and bring the income to help increase the life quality of disadvantaged communities.

Project Scope and Objectives

This project is setting Miami, Florida, and Phoenix, Arizona, as two target cities for constructing solar canopy. The target locations of this project are two public schools, Madison Highland Prep/Madison Park Elementary School in Phenix and Hialeah-Miami Lakes Senior High School in Miami. The overall idea is to construct solar canopies above the outdoor basketball courts of these schools and provide shade for students and electricity for the school. This project plans to use the grid-connected system. By providing shade for students and reducing electricity consumption of the schools, the economic pressure on those communities could be decreased.

Limitations

One critical limitation of this project is the feasibility. Even though this project is set up not as one entire conceptual idea, the overall feasibility of this project could face multiple challenges in different processes. Converting this project into reality may need cooperation of varied sectors including government, founders, and construction companies. Coordination between those sectors could be time consuming and non effective.

The source of funding is anticipated to be limited. For low income communities, funding is usually given for areas that aid schools the most, such as free lunches for students, new and up-to-date textbooks, and classroom renovations. As mentioned above, the involvement of the

government and/or non-profit organizations would be the most realistic approach, but the incentive of electricity generation to lower the electric bill could be enough to sway the schools in question to fund such a project.

The willingness of the local residents is also very unpredictable for this project. The unwillingness of this project, based on the previous two reasons, can be that the local government does not have such a budget to process the project. If the government does, the welfare of the community will get lower than before. The unwillingness can also come from residents. We don't have the confidence to say that residents do not want sun when they are having sports. Before the project becomes a reality, we would need more surveys in this community.

The grid-connected system can play a role in peak regulation. For the grid connection of photovoltaics in this scheme, a local power grid permit is required. The estimated total power generation and investment return in this scheme are obtained through historical data, and the actual project will generate corresponding data and price deviations according to the location and roof conditions.

Market Analysis

Economics

The biggest factor in determining whether or not communities and facilities choose to switch to solar energy is the cost of investment. Solar is meant to provide the same amount of electrical energy as other unrenewable sources while decreasing the operating and capital costs altogether. In short: its utilization must provide economic benefit to the buyer. Some things to consider in a solar investment include its payback period, expected life, government incentives, and maintenance costs. Payback Period refers to the number of years required to recover the original cash investment. The payback period will vary depending on the expected life of the panels and the number of panels. The average expected life of the high quality solar panels is about 30

years, so under perfect weather conditions, maintenance costs wouldn't come into play until 30 years after.

Green energy is something that various countries around the world are trying to get its citizens to convert to, but it may not be affordable or practical to everyone. To solve this predicament, most federal, state and local governments offer green energy incentives to citizens who are interested in converting to green energy. One of the most popular incentives is Net Metering, which is a policy that reduces a home's electricity bill costs depending on how much their solar system or renewable energy source produces. The closer the energy produced is to the amount of energy used, the less you have to pay. There are plenty of other incentives to choose from, including a 30% tax credit, low-interest loans, and grants (grants are only for large scale renewable energy projects). As was said previously, most states have incentives for switching to renewable energy, so the number of incentives a state offers differs from state to state. California has the most incentives to offer with a grand total of 168 across the state, while Kansas has the least incentives with 12. The number of incentives can certainly play a role in how many people convert to renewable energy, especially to those with financial trouble. As of now, these incentives go towards the implementation of the solar system itself. If a structure such as a canopy were to be constructed to put the system on top of it, that would have to be financed separately.

Case study: Sultan Qaboo University

After reviewing a few cases of solar PV projects, the Qaboo University sports complex was chosen for a case study analysis due to its applicability to our project. The Qaboo University delves into the solar panel design, the economics of the project, and the decision framing behind the project.

Located in the Middle East, Sultan Qaboo University has a lot of solar resources available, being an area with one of the highest solar energy densities in the world. Measured solar irradiation in the area has shown values of 5500-6000 W/m² in July and 2500-3000 W/m² in January. Additionally, Oman has been looking to incorporate more renewable energy into their portfolio with the goal of being 30% renewable in the electricity sector by 2030 (3). Currently, 97% of the electricity in Oman comes from Natural Gas (Ahshan et al., 2019).

Ahshan et al explains the design and analysis of this project beginning with the methodology. The flowchart behind building the PV system can be seen in Figure 1. The procedure described follows a similar approach our project team took as we began to decide where and how to implement our project. Some of the steps most applicable to our conversations include: “Site resources availability,” “PV system design and size,” “Economic performance and evaluation using economic models.” The flowchart also considers whether or not the system will have a connection to the grid as they plan on selling any electricity produced that is not consumed on site.

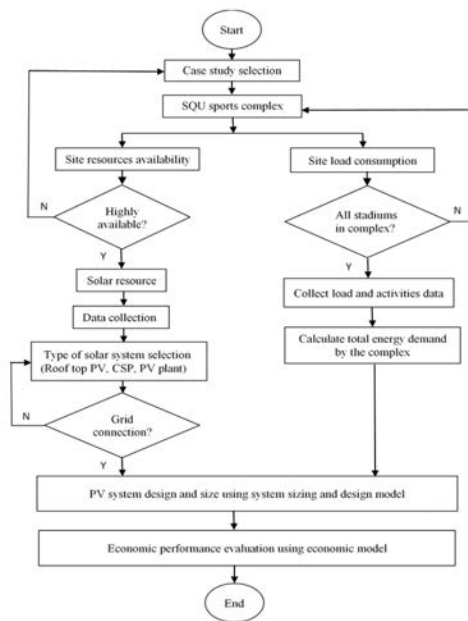


Figure 1. Flowchart Behind Building the PV System

In order to determine the site resource availability at Sultan Qaboos University, the temperature and solar irradiation data was collected from a location 1.5 km away (Ahshan et al., 2019). Figure 2 & 3 below show the monthly variation of this data. Figure 4 is a result of using this information to determine the average derating factor of each month.

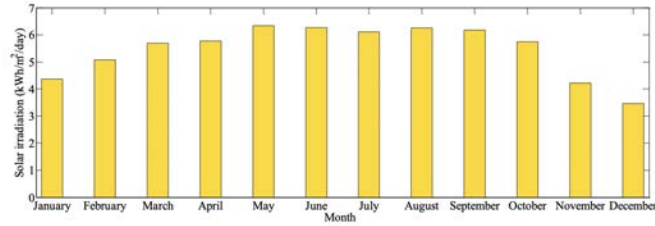


Figure 4. Monthly average solar irradiation available in the SQU campus

Figure 2. Monthly Average Solar Irradiation Available in the SQU Campus

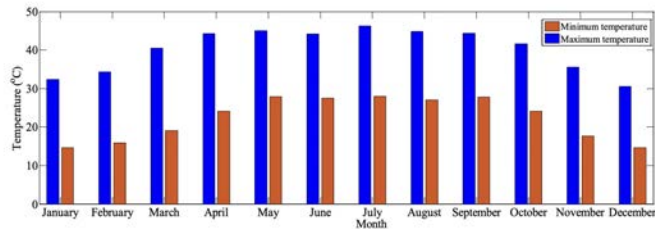


Figure 5. Variation in temperature profile for each month in SQU campus.

Figure 3. Variation in Temperature Profile for Each Month in SQU Campus

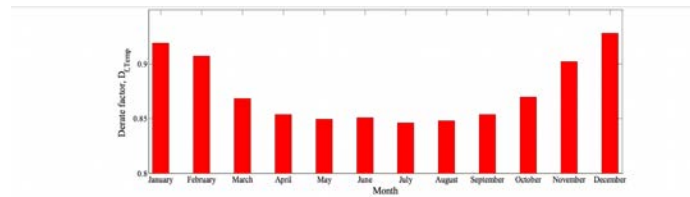


Figure 7. Variation in derating factor due to variation in the temperature.

Table 6. Module output voltage considering the temperature effect

Weather condition	Ambient temperature	Module output voltage without temperature effect	Module output voltage with temperature effect	Number of modules per string
Coldest	14.67°C	37.96 V	37.51 V	12-20
Hottest	46.32°C	37.96 V	33.75 V	14-23

Figure 4. Variation in Derating Factor Due to Variation in the Temperature

Data was also collected to determine the load demand of the different courts and fields in the sports complex. Combining the data and the calculations we can see how much energy will be consumed by the sports complex, how much the system will produce, and consequently how much must be sold or bought. The results can be seen in Figure 6. During the months of January, February, October, November, and December the sports complex is consuming more energy than it is producing. During the other months, it produces more than it consumes. From April to

September, the sports complex does not need to consume any electricity and can sell the entire production for those months.

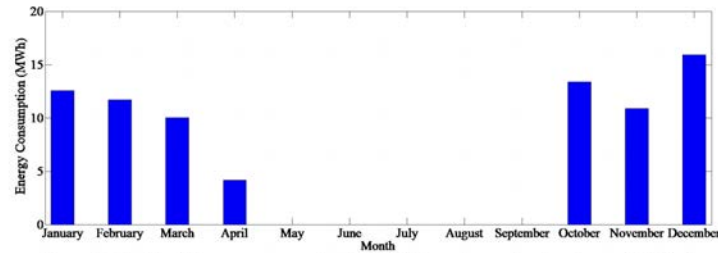


Figure 5. Monthly Total Energy Consumption by the SQU Sport Complex: There is no Activity in the Complex from May to September, for which the Energy Consumption is Zero

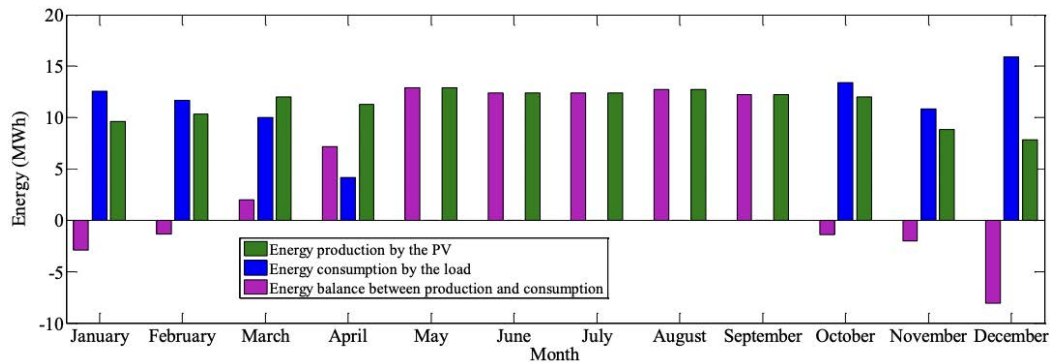


Figure 6. Energy Performance of the Designed PV System for the SQU Sport Complex

The PV system calculations described by Ahshan et al. are summarized below. The following equations were used to eventually determine the output voltage of a module in this location throughout the year.

$$P_{DC} = \frac{E_{load}}{D_f P_{sh} N_{day}} \quad (1)$$

$$T_{cell} = T_A + \left(\frac{T_{NOCT} - 20^\circ C}{S_{NOCT}} \right) \times S_{site} \quad (2)$$

$$P_{module} = \beta \times (T_{cell} - 25^\circ C) \quad (3)$$

$$D_{f,Temp} = 1 - P_{module} \quad (4)$$

$$D_f = D_{f,Temp} \times D_{f,comp} \quad (5)$$

$$A_{PV} = \frac{P_{DC}}{\alpha S_{STC}} \quad (6)$$

$$n_{module} = \frac{A_{PV}}{A_{module}} \quad (7)$$

$$V_{mo} = V_{mo,STC} \times (1 - \kappa (T_{cell} - 25^\circ C)) \quad (8)$$

- (1) P: Power generated (kW), E: energy load demand in one year (kWh/year), Df: derating factor, Psh: peak sun hour, N: #of days in a year
- (2) Ta: Ambient temperature, Tnoct: normal operating cell temperature, Site: average solar intensity,
- (3) Pmodule: reduction in max power output of module, B: reduction in maximum power per deg C temp variation
- (4) Derating Factor from temp variation
- (5) Total derating factor
- (6) Apv: Area required for panel installation, Sstc: solar intensity at standard testing conditions (kW/m²), alpha: module efficiency
- (7) Number of Modules required
- (8) Module Output Voltage

Ahshan et al also describes an economic model used to determine the project cash flow. The model uses the assumptions that there is a \$700/kw investment cost, O&M costs are 0.22% of the initial investment yearly, and the project lifetime is 25 years (Ahshan et al., 2019). The following equations are then used to create the cash flow.

Payback Period: $PP = \text{Initial Capital Cost} / \text{Annual Cash Inflow}$

Net Present Value: $NPV = \sum (C_n / (1+d)^n - C_0)$

Internal Rate of Return: Set $NPV = 0$ and solve for IRR

Profitability Index: $PI = \text{Net Present Value} / \text{Initial Investment Cost}$

The results of this model can be seen below. The first figure shows a scenario in which there was no loan taken out for the project (discount rate $d = 0\%$) while the second figure shows a scenario in which a loan was taken out with a discount rate $d = 6.5\%$. The payback period in the first scenario is 9 years while the payback period is slightly longer at 14 years for a project with a discount rate (Ahshan et al., 2019).

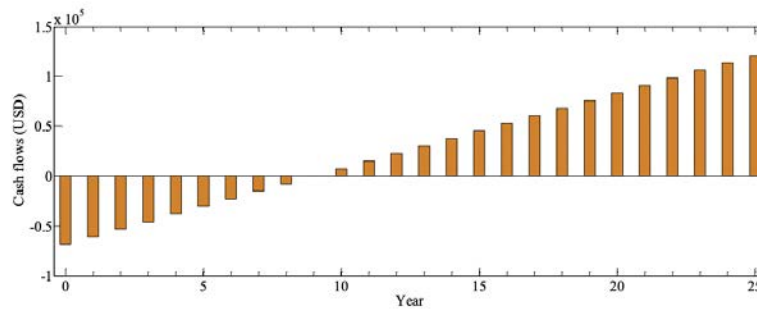


Figure 7. Cash Flow Performance Considering the Discount Rate, $d = 0\%$

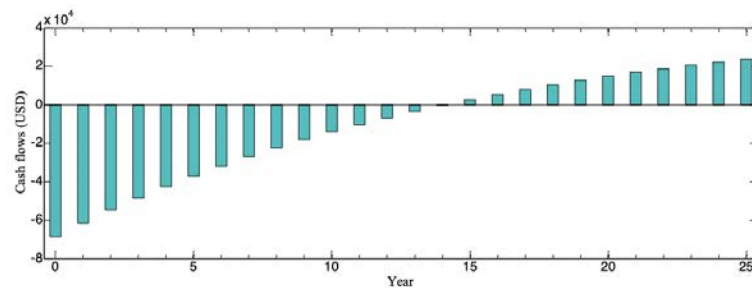


Figure 10. Cash flow performance considering the discount rate, $d = 6.5$

Figure 8. Cash Flow Performance Considering the Discount Rate, $d = 6.5\%$

How Shade Decreases Temperature

Before looking into the economic benefits brought by building solar canopies to communities, a more fundamental advantage is the shaded area it will create for exercise or parking space. Wet-bulb globe temperature (WBGT) is the best measurement of the external thermal load when exercising outside. It depends on multiple factors: temperature, humidity, air movement, and solar radiation. The solar radiation will increase the heat absorption during exercise under the sun, thus increasing the risk of heat stroke. The solar radiation also warms up vehicles that are exposed to it. The solar radiation heats up the exterior surface of vehicles and then the interior. The temperature inside of the car will be much higher than the surrounding air temperature. As of 2020, 38 children die each year, on average, from heat stroke from being left in cars.

The reason why shade is important is that it blocks solar radiation from heating up the ground, skin, and cars directly. Due to the movement of air and temperature equilibrium, air temperature inside and outside of the shaded area is the same unless the shaded area is very large, which is not possible to build in our case. In this project, we assume air temperature is the same everywhere. However, shades have a significant effect on surface temperature. A study of tree canopy reveals that the temperature differential between sunlit and shaded surfaces is large and varies depending on surface type, but quantity (A_c) and density (LAI) of tree shades has little effect on temperature differential (ΔT_s) between sunlit and shaded surface temperatures.

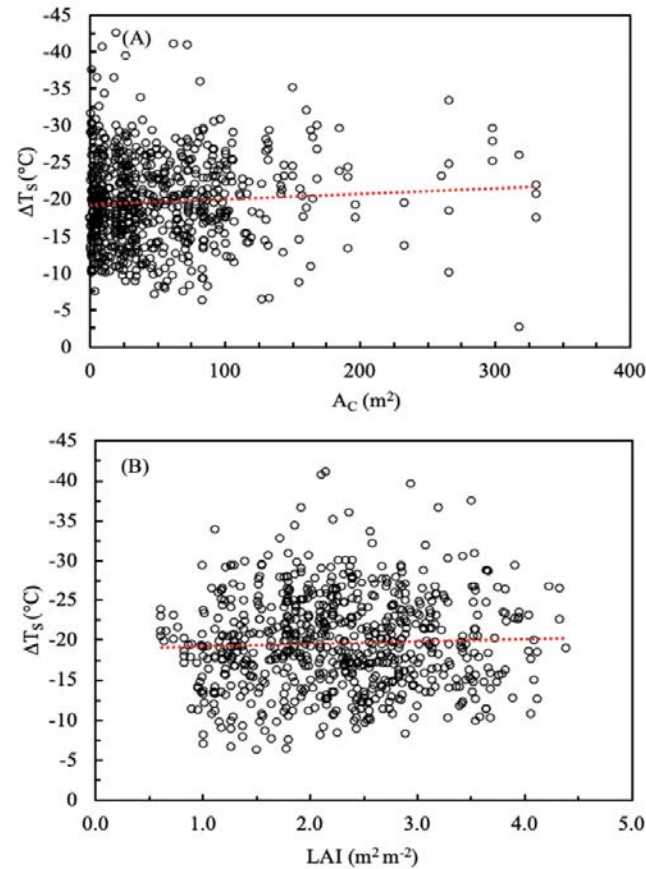


Figure 9. Relationships between tree crown characteristics and surface cooling, calculated as a differential between the surface temperature in the sun and shade of a given surface type (ΔT_s)

The findings will potentially support the possibility of semitransparent solar canopy, as it may have the same ability to reduce surface temperature and provide necessary sunlight at the same time.

Modeling “insolation” using Rhino

By loading the Climate Studio package with rhino 7, detailed weather data for most cities and regions worldwide are available. Comparing the solar irradiance and other data of the four cities investigated in this project can infer or prove the feasibility of this photovoltaic project in the target city.

Global Horizontal Irradiance (GHI) is the total amount of solar radiation that is received per unit area by a surface that is always positioned in a horizontal manner. Direct Normal Irradiance (DNI) is the total amount of solar radiation received per unit area by a surface that is always perpendicular to the sun rays that come in a straight line from the direction of the sun at its current position in the sky. Diffuse Horizontal Irradiance (DIF) , also known as (DHR), presents the amount of radiation received per unit area by a surface that does not arrive on a direct path from the sun, but has been scattered by molecules and particles in the atmosphere. GHI and DIF are referred to a surface horizontal to the ground, while DNI is referred to a surface perpendicular to the Sun. Higher values of DHR/GHI ratio represent a higher occurrence of clouds, higher atmospheric pollution or higher water vapor content. The difference between the dry bulb temperature and the wet bulb temperature can help to infer the local air humidity. The larger the temperature difference between the dry and wet bulb temperatures, the lower the humidity in the air.

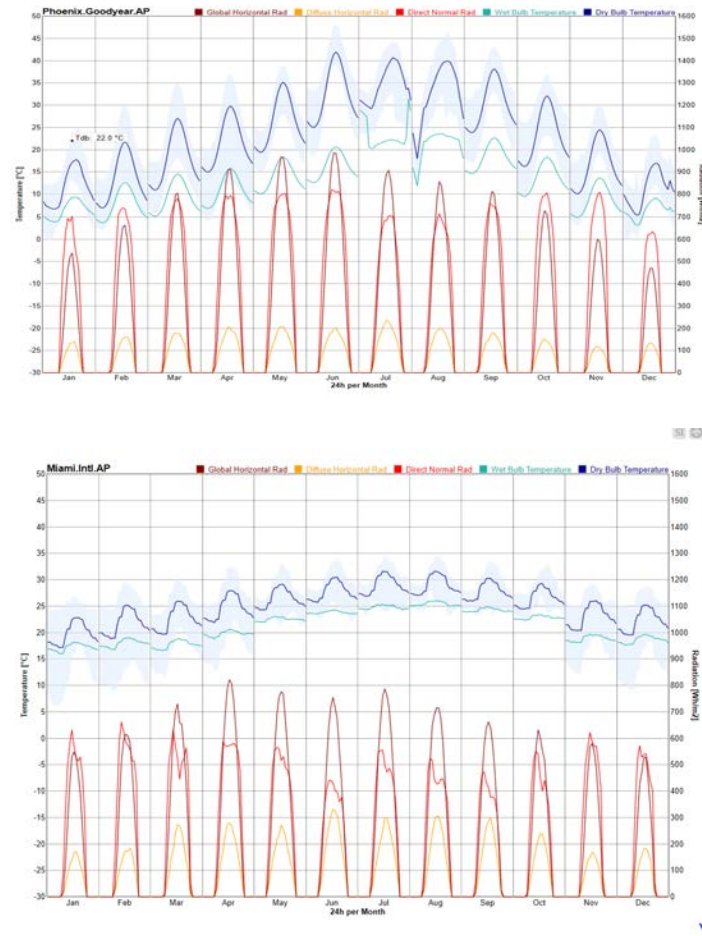


Figure 10. Diurnal Average

Comparing the detailed lighting data of the following cities, Phoenix's annual average temperature and GHI are higher than Miami's, indicating that the city's light is more suitable for the operation of solar panels than other cities. In addition, the significant temperature difference between the dry and wet bulbs in the local area indicates that the air humidity is low, the precipitation and extreme weather are less, and the photovoltaic system can generate electricity for a longer time and efficiency. One of the other three target cities is selected as a comparison and reference to Phoenix. The data, such as light and the average temperature in Miami, are more suitable for the operation of the solar photovoltaic system.

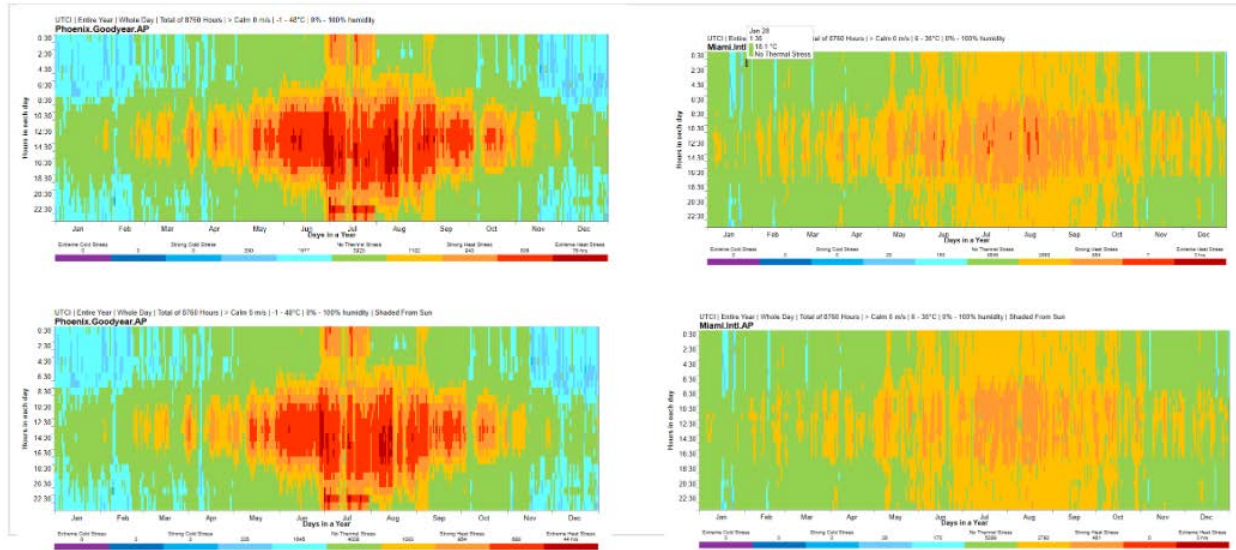


Figure 11. Temperature Difference Between Shaded Area and Unshaded Area in Phoenix and Miami

As shown in Figure 11, the temperature of the two cities will be significantly reduced under the shadow, which confirms the feasibility of this project. Solar roofs can effectively reduce air temperature and reduce solar radiation.

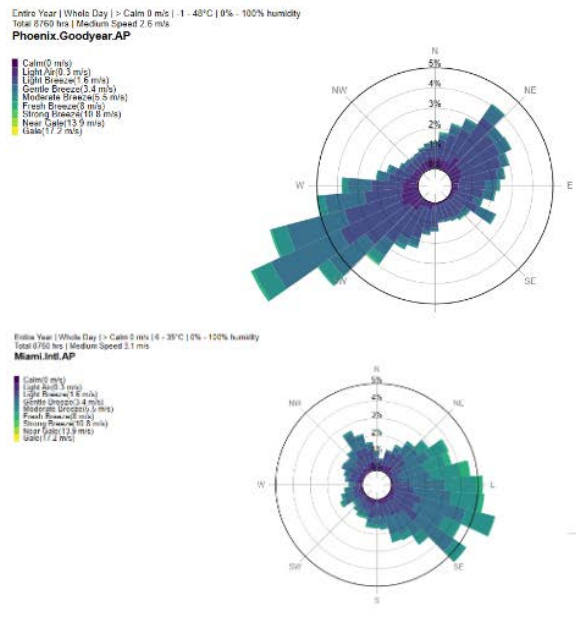


Figure 12. The Rose Wind Diagram of Phoenix and Miami

The Rose Wind Diagram is drawn based on the percentage data of each wind direction in the region for many years, which can intuitively reflect the wind speed and direction of a region. Lower wind speed can reduce the probability of damage to photovoltaic panels and thus reduce operation and maintenance costs. Wind direction may also affect the stable operation of photovoltaic systems. Since most photovoltaic panels face due south, strong south or north winds may affect the stability of photovoltaic panels and buildings. As shown in Figure 12, the darker the color, the lower the wind speed in the wind direction. Phoenix and Miami have lower wind speeds, and the southeast and southwest wind directions have less impact on photovoltaic panels, indicating that wind direction and wind speed have less impact on photovoltaics in these two regions.



Figure 13. Grid-Connected Commercial System

The electricity produced by this project will be connected to the public power grid. The grid-connected photovoltaic power generation system can convert the DC power output by the solar cell array into AC power with the same amplitude and frequency as the grid voltage and realize the connection with the grid to transmit electricity to the grid. . When the sunshine is strong, the photovoltaic power generation system can supply the excess power to the grid while supplying power to the project's electrical equipment.

Countries Implementing Solar PV

Global application of solar power is having an obvious increasing trend led by major players including China, the USA, and Europe. The following paragraphs will destrate data from the USA, China, Europe, and Japan as representatives for the global growth Solar PV implementation.

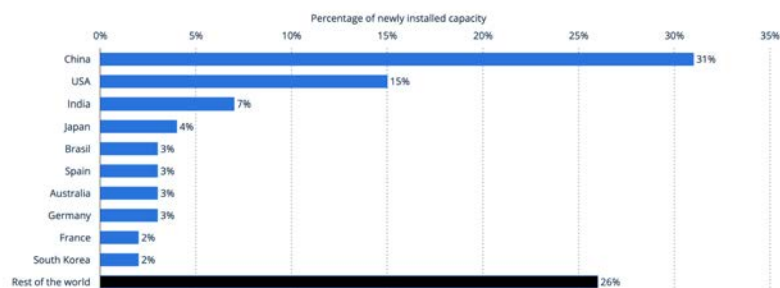


Figure 14. Percentage of New Installed Solar PV Capacity Worldwide in 2021, by Country (Statista)

The USA

The USA has been one of the leading countries in applying renewable energy and solar power is experiencing great growth in recent years. In 2021, the net solar power generation in the United States reached its highest point yet at 114,678 million kWh of solar thermal and photovoltaic power. The third quarter of 2020 proved to be the greatest first quarter for the U.S. solar PV installation.

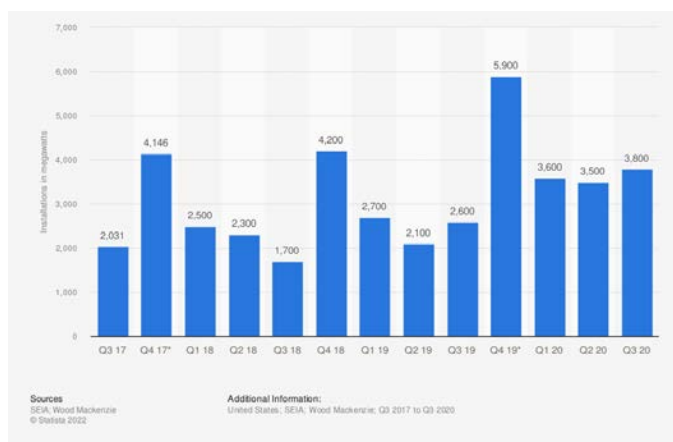


Figure 15. Capacity Addition of Solar Photovoltaic Units in the US from Q3 2017 to Q3 2020 in MW (Statista)

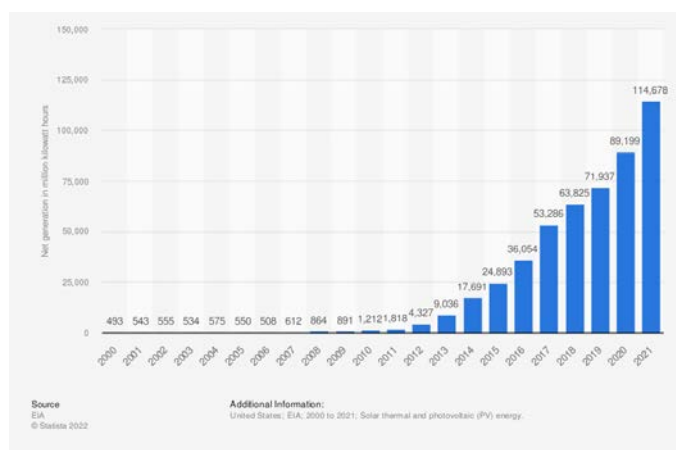


Figure 16. Solar Power Net Generation in the US From 2000 to 2021, in Million kWh (Statista)

China

China is the leading country for the renewable energy market, including solar energy. As the country implements the largest amount of solar power, China's solar power generation reached nearly 330.7 terawatt hours in 2021, which has increased by 20.9 percent in capacity compared to the previous year. As of 2021, China has an installed solar power capacity of over 3000 gigawatts. China has made enormous strides in building up its solar power capacity within the past decade, growing cumulative capacity from only 4.2 gigawatts in 2012 to 306.56 gigawatts in 2021.

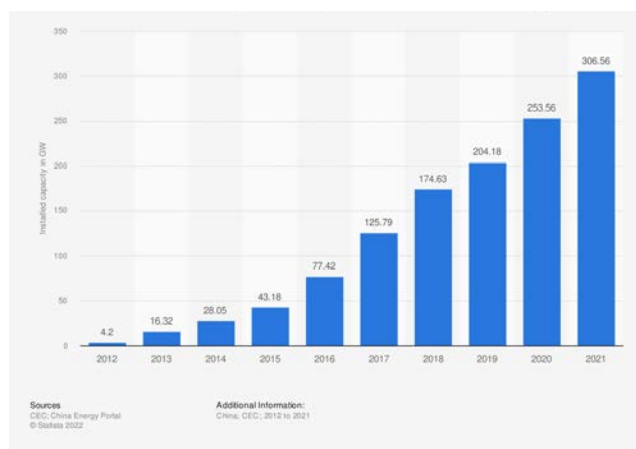


Figure 17. Cumulative Installed Solar Power Capacity in China from 2012 to 2021 in GW
(Statista)

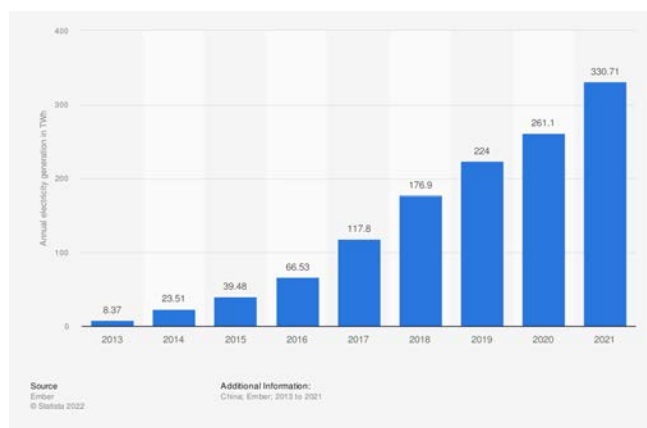


Figure 18. Annual Power Generation from Solar Power in China from 2013 to 2021 in terawatt hours (Statista)

Europe

The 27 European Union members added 22.8 gigawatts worth of solar photovoltaic capacity in 2021, up from 15.6 gigawatts in 2019. In 2021, Germany was the country with the greatest electricity production volume among all EU members, at 49,992 gigawatt hours.

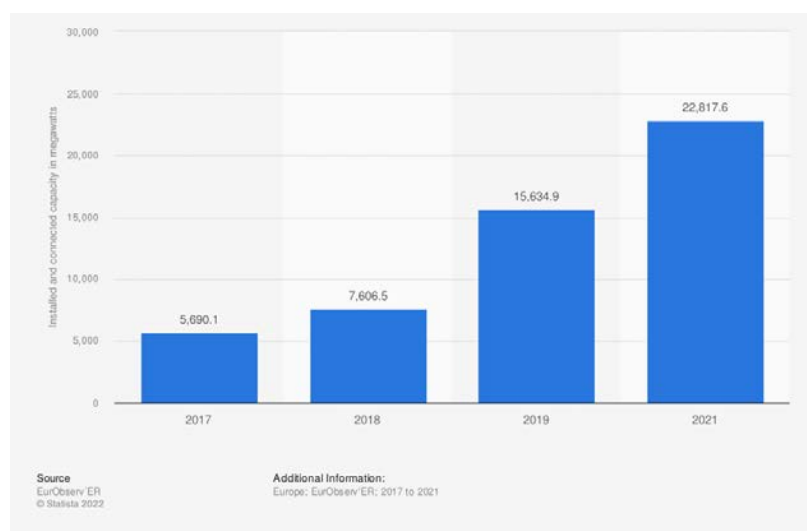


Figure 19. Annual Net Solar Photovoltaic Capacity Addition Installed in the European Union (EU 27) from 2017 to 2021 in MW (Statista)

Japan

To reduce greenhouse gas emissions and be less dependent on fossil fuel imports, the Japanese government currently aims to increase the use of renewable energy sources. In the fiscal year 2020, approximately 79 terawatt hours of electricity were generated from solar energy in Japan, showing a significant increase from around five terawatt hours in fiscal 2011. In 2021, the generation capacity of solar energy in Japan amounted to approximately 74.2 thousand megawatt.

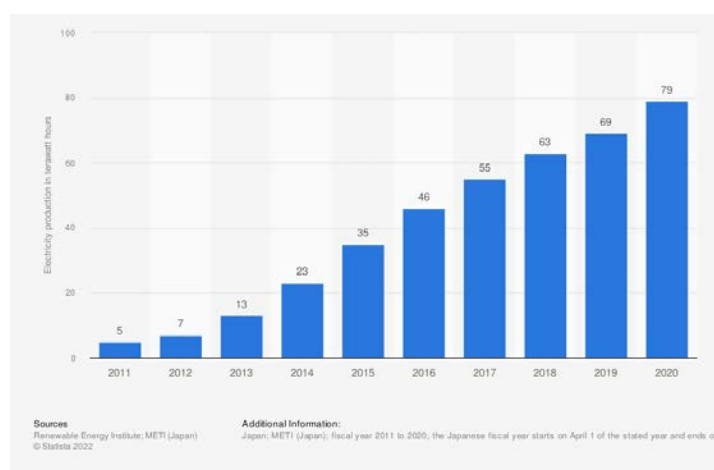


Figure 20. Electricity Production from Solar Energy in Japan from Fiscal Year 2011 to 2020 in terawatt hours (Statista)

Potential Solar Canopy Location

Phoenix, Arizona

According to the United States Census Bureau, in 2020, the population of Phoenix was 1,658,000. By using PV Watts, we get that 1 kW at 33.45 degrees (latitude of Phoenix) would produce 1,741 kWh/year, which is the highest production from all four cities. The following two graphs are from the National Centers for Environmental Information. The first one shows the monthly average maximum and minimum temperatures, and the second one is the monthly average daylight.

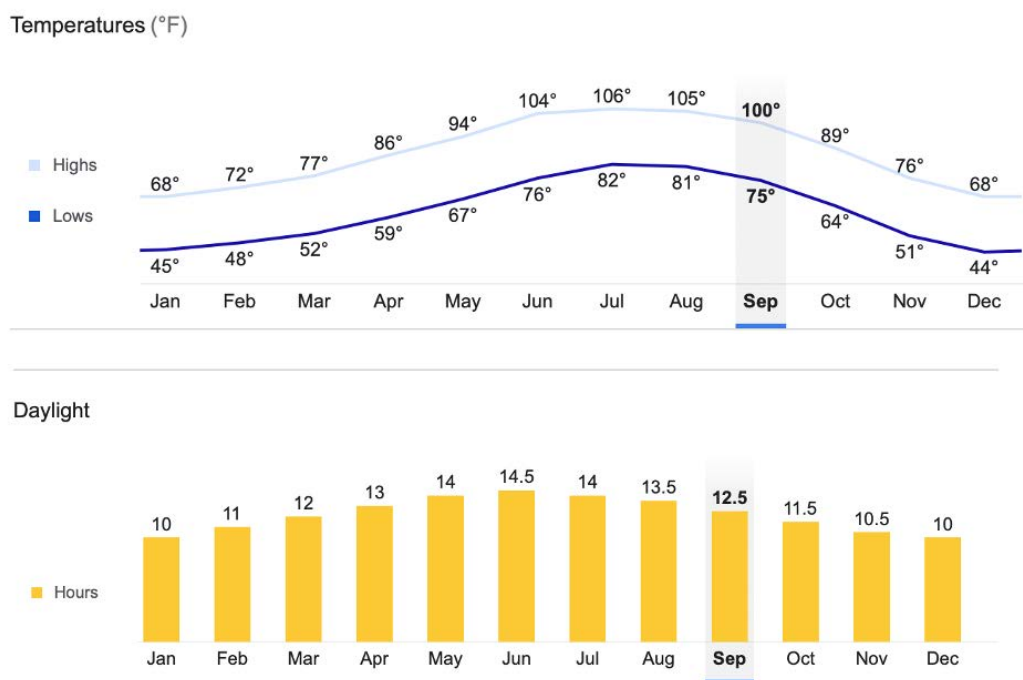


Figure 21. Phoenix's Average Temperature and Daylight Hours Throughout the Year

Some potential locations for the solar shade canopies in Phoenix would be a bus stop, the State Farm Stadium (which is technically in Glendale), and a children's playground.

However, some concerns about choosing this city are that it gets extremely hot during the summer so people might decide not to be outdoors at all. On the other hand, it is still hot all year round so it would still be useful, and will generate a lot of energy.

Chicago, Illinois

According to the United States Census Bureau, in 2020, the population of Chicago was 2,699,000. By using PV Watts, we get that 1 kW at 41.9 degrees (latitude of Chicago) would produce 1,343 kWh/year, which is the lowest production from all four cities. The following two graphs are from the National Centers for Environmental Information. The first one shows the monthly average maximum and minimum temperatures, and the second one is the monthly average daylight.

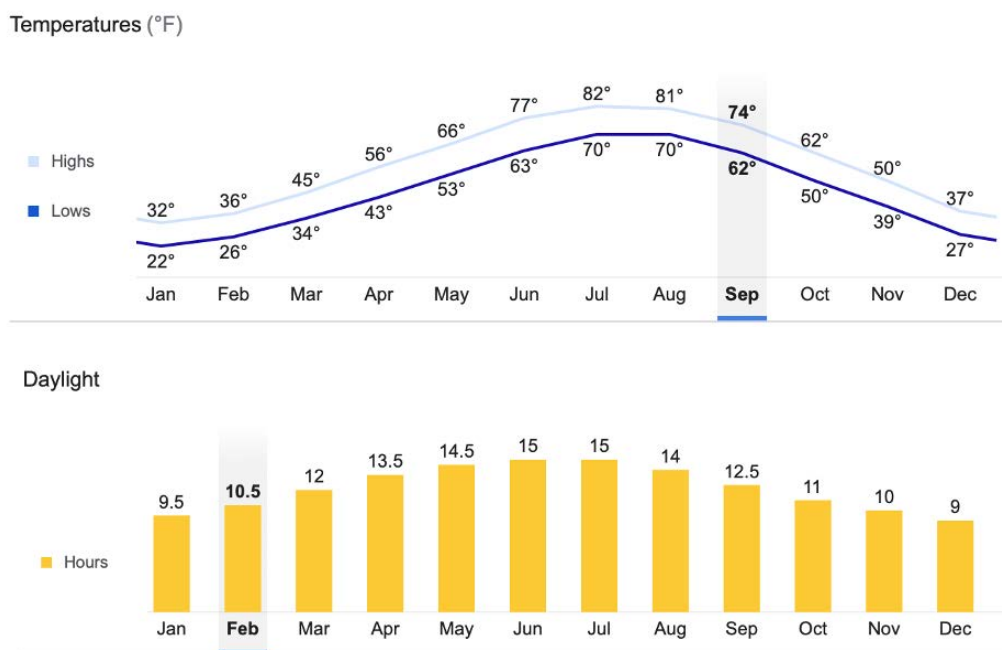


Figure 22. Chicago's Average Temperature and Daylight Hours Throughout the Year

Some potential locations for the solar shade canopies in Chicago would be a bus stop or train station. Another option would be in a children's playground or basketball court in the suburbs.

Chicago is the only city from the four we chose that gets snow, this means that the canopies are going to be used to cover from snow rather than heat, and that there is a possibility that the solar panels remain covered in snow for a long period of time. Furthermore, during the summer, the heat is not as extreme as in the other cities.

Miami, Florida

According to the United States Census Bureau, in 2020, the population of Miami was 461,080. By using PV Watts, we get that 1 kW at 25.8 degrees (latitude of Miami) would produce 1,580 kWh/year, which is the second highest production from all four cities. The following two graphs are from the National Centers for Environmental Information. The first one shows the monthly average maximum and minimum temperatures, and the second one is the monthly average daylight.

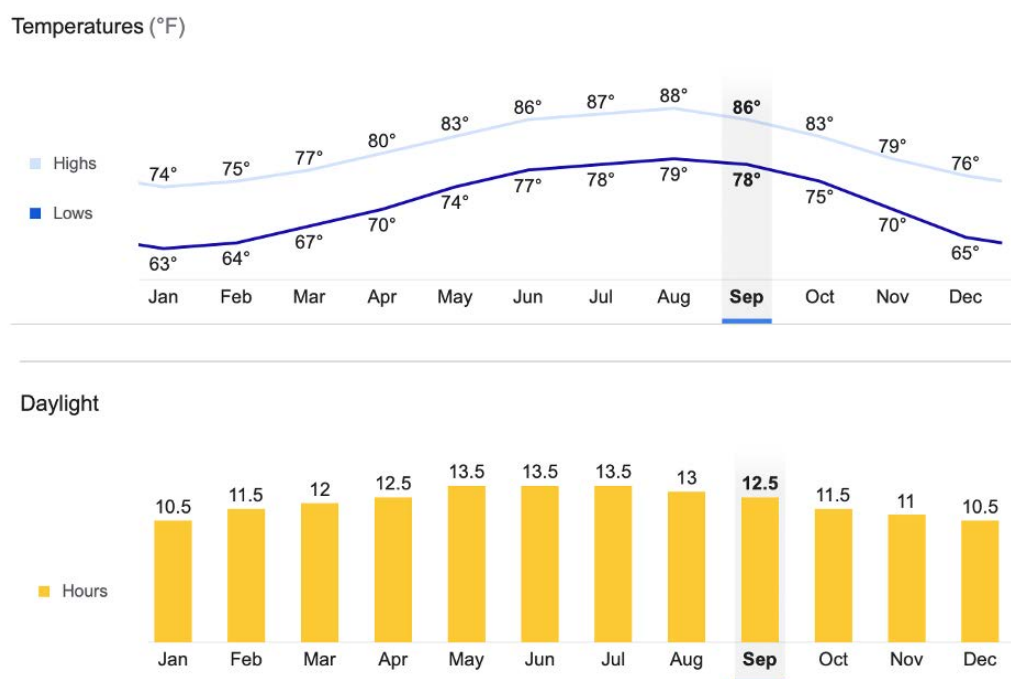


Figure 23. Miami's Average Temperature and Daylight Hours Throughout the Year

Some potential locations for the solar shade canopies in Miami would be a bus stop, outdoor mall (eg: The Shops at Pembroke Gardens), a children's playground or outdoor basketball court. Miami is hot all year round so providing shade for public areas may be helpful; however, it also has hurricanes so the structure should probably be stronger than in the other locations.

Atlanta, Georgia

According to the United States Census Bureau, in 2020, the population of Atlanta was 467,642. By using PV Watts, we get that 1 kW at 33.7 degrees (latitude of Atlanta) would produce 1,453

kWh/year. The following two graphs are from the National Centers for Environmental Information. The first one shows the monthly average maximum and minimum temperatures, and the second one is the monthly average daylight.

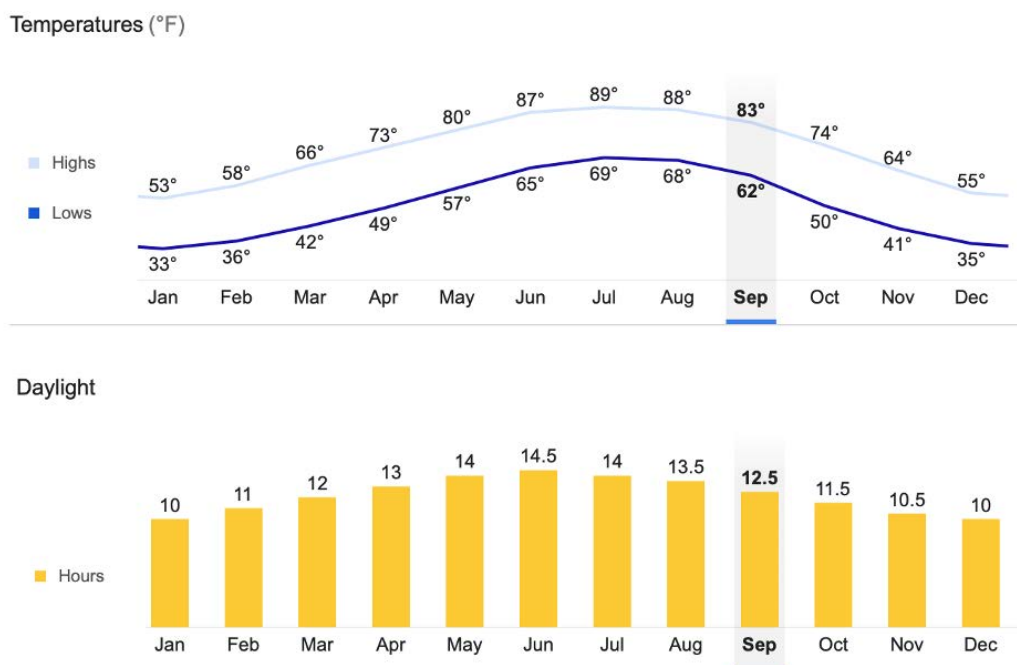


Figure 24. Atlanta's Average Temperature and Daylight Hours Throughout the Year

Some potential locations for the solar shade canopies in Atlanta would be a bus stop or children's outdoor playground.

Atlanta has the highest poverty rate from all four cities which means that people might need it more here. Regarding the weather, it is similar to Miami but with colder winters.

Overall Analysis

- Phoenix seems to be a reasonable choice due to its extreme heat as well as its high annual energy production per kW installed.
- Chicago would not be a smart choice since the snow and extreme cold would signify a lower production as well as a lower need for sun protection.
- Miami might be a good choice since it is warm all year round and has the second highest energy production per kW installed. However, we should consider the hurricanes too.

- Atlanta may also be a good choice since the summer is hot and the winter is not extremely cold. Energy production is lower than Miami but there is a lower risk of hurricanes.

Miami

Solar Resource

As seen in the market analysis, Miami has between 10.5 and 13.5 daylight hours per day throughout the year. Due to its long sunlight hours, its average annual solar production per kW installed, with the panels tilted at 5 degrees South (angle chosen for the structure), would be 1,487 kWh. If the panels were placed to optimize production, they would be tilted at 26 degrees, about Miami's latitude, which would produce 1,549 kWh/year per kW installed.

Location

The specific location chosen for Miami is Hialeah Miami Lakes Senior High school, located at 7977 West 12th Avenue, Hialeah, Florida. This is a public community school that has 96% of minority students and a majority of them are receiving Federal and local subsidies (Hialeah Senior Official Website).

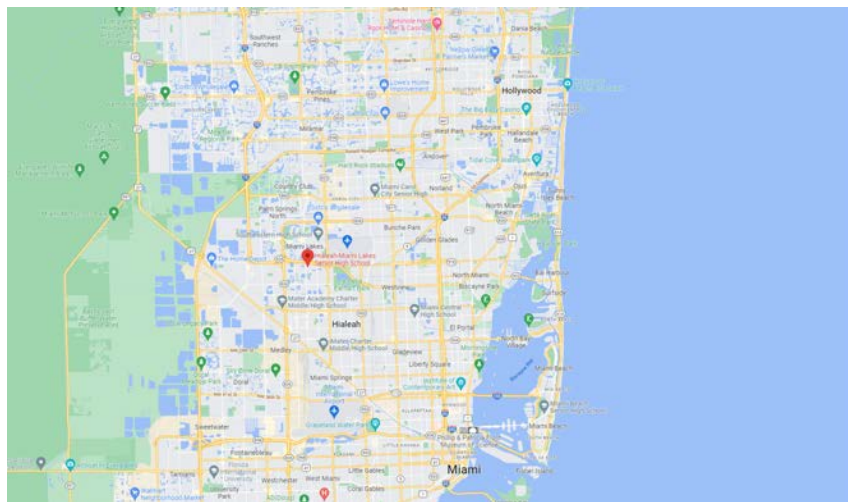


Figure 21. Location of Hialeah Miami Lakes Senior High School



Figure 22. Location of the Basketball Courts

The project is targeting the basketball courts on the north side of the campus. There are four basketball courts in total, yet there would be only the middle two covered by the intended project. This is aiming to offer students with options to choose from, from whether to play with no cover on sunny warm days or with cover on rainy days. Covering the two basketball courts on the edges also avoids potential effects on surrounding vegetation. These basketball courts are facing north and south which minimizes the impacts of the building on both north and south. The construction will have a minimum height of 9 meters and the buildings on both the north and south sides are less than 9 meters in height and the impact of these buildings will be minimal. The location of this senior high school is relatively inland in the Florida region, which is well known for hurricanes. By having the structure relatively inland, the potential damage caused by hurricanes could be reduced.

Design Inspiration

In terms of coming up with a design for the solar canopy, there were two main locations that were used. The first location is Silverbell Park, which is located in Tucson, Arizona and has its own basketball court with a solar canopy above it. Being that it's in the same state, it makes the chances of constructing another in Phoenix much more likely. The project was constructed by the Solon Corporation, a company based in the Southwest United States who is a leading provider of

large commercial and utility-scale photovoltaic system solutions. There is reason to believe that it was the state or local government's idea to have such a canopy installed, but that is uncertain. The main aspects that were taken into consideration when designing the Phoenix Canopy was the tilt angle and the canopy's support. Any sort of tilt angle adds to the overall solar absorbance from the panels, which then leads to more energy generation. The slight tilt would also keep rainfall from staying on top of the canopy and increase panel deterioration. An additional aspect that we kept in mind from this structure was the supports. The beams go under the canopy from the outer edges, seemingly to give more support towards the middle of the canopy. We would speculate that a semi-strong gust of wind would destabilize the canopy, so it would be worthwhile to contact the Solon Corporation regarding their design for their canopy and how such a design holds up in Arizona's weather conditions.



Figure 23. Silverbell Park's basketball solar canopy in Tucson, Arizona.

In addition to the Silverbell Park canopy, we also took inspiration from the Gando Secondary School's building in Burkina Faso, West Africa. The main aspects that were taken from this institution were its adobe elements and the raised roof with a mesh structure. In the context of the school, the raised roof allows for sunlight to enter the building easily, making sunlight the only necessary light source during instruction periods. In a similar manner, adding a raised roof with a

mesh structure allows more sunlight to come in. The school's outer walls are completely made from adobe, which is a very insulating material and keeps the inside of the building cooler during hot temperatures, which Burkina Faso tends to have regularly. Phoenix has very similar weather conditions to Burkina Faso, so the addition of adobe elements would be helpful. By adding some adobe to the sides, it would help with keeping the temperature under the canopy slightly cooler, which is always better for the community and players who use the court.



Figure 24. Gando Secondary School in Burkina Faso, West Africa.

Structure and Design

Since the solar canopy located in Miami is designed from North to South. To have more efficiency for solar energy. The design of the structure roof should tilt 5 degrees from the origin horizontally.

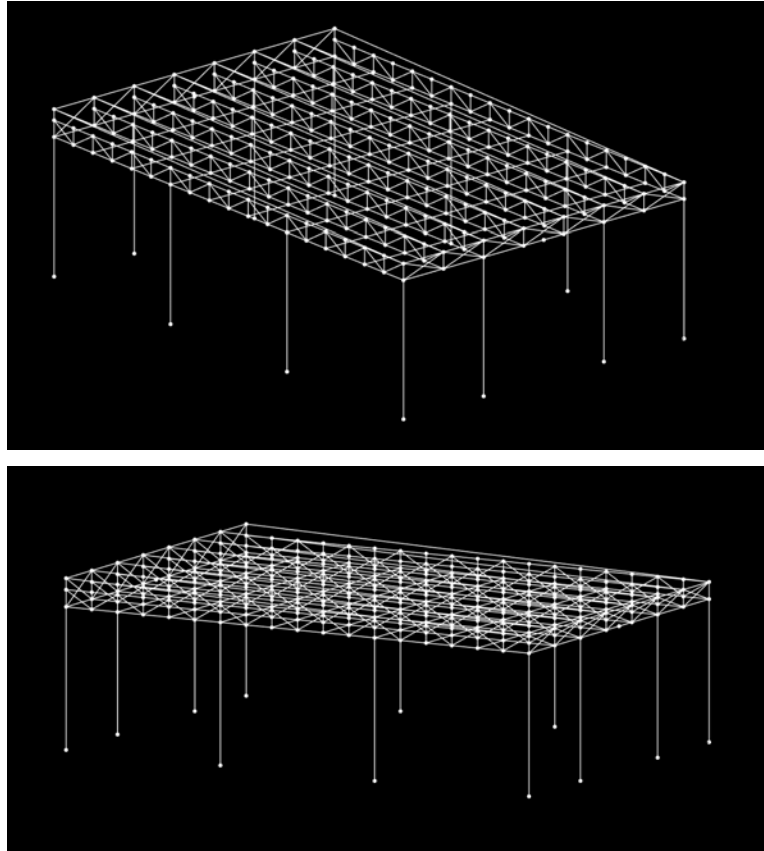


Figure 25. Model of the Structure

The figure provides a brief understanding of how the structure should look from two angles. In addition, the Miami region has several hurricanes during the year. To have a strong wind resistance to keep the roof of the structure from being overturned, the wind resistance structure under the ceiling is necessary. As a result, 7760 linear feet of steel are required to build the system. The weight of the steel structure will be 197,842.58 lbs.

$$\textit{The Weight of Steel: } 7760 \text{ linear ft} * 22\text{lbs} + (91.86\text{ft} * 98.42\text{ft}) * 3\text{lbs} = 197,842.58 \text{ lbs}$$

The canopy will cover two basketball courts with a total area of 9040.86 square feet. The roof will carry 765 pieces of solar panels to produce solar energy. The location of Hialeah Miami Lakes Senior High School has average annual production for a 1-kilowatt solar panel which tilts 5 degrees at 1,487 kWh per year (PVWatts - NREL ., 2022). Each solar panel has 200 W and 26.46 lbs. The total weight of the solar panels will be 20,241.9 lbs.

$$\textit{The Weight of Solar Panels: } 765 \text{ panels} * 26.46 \text{ lbs} = 20,241.9 \text{ lbs}$$

The total weight solar canopy structure for Hialeah Miami Lakes Senior High School will be 218,084.28 lbs.

$$\textit{The Total Weight of Structure: } 20,241.9 + 197,842.58 = 218,084.48 \text{ lbs}$$

Energy output for the solar system will be 227,529 kWh per year. With the loss of energy during the transition inside the solar panels, the capacity factor of the solar panels will be 16.98%. If we do not consider the energy loss, the energy output will be 153 kW when the solar panels are installed.

$$\textit{Energy Output without Energy Loss: } 765 \text{ panels} * 200W = 153 \text{ kW}$$

$$\textit{Total Annual Production: } 227,529 \text{ kWh}$$

$$\textit{Capacity Factor: } 227,529 \text{ kWh} / (153 \text{ kW} * 24 \text{ hr} * 365 \text{ days}) = 16.98\%$$

Cost

Before estimating the Levelized cost of electricity (LCOE), we assume a discounted life of 20 years and a discounted rate of 5%. It is necessary to calculate the structure cost because the structure cost will affect the estimation of LCOE. The total cost of steel is \$116,400, the cost of solar panels is \$191,242.35, the cost of framework is \$99,440, the cost of roof is \$135,612.9, and the total fixed cost of the structure is \$542,695.25.

$$\textit{Total Cost of Steel: } 7760 \text{ linear ft} * \$15 = \$116,400$$

$$\textit{Total Cost of Solar Panels: } 765 \text{ panels} * \$249.99 = \$191,242.35$$

$$\textit{Total Cost of Framework: } 4.52 * \$22,000 = \$99,440$$

$$\textit{Total Cost of Roof: } 9040.86 \text{ sqft} * \$15 = \$135,612.9$$

$$\textit{Total Fixed Cost: } \$116,400 + \$191,242.35 + \$99,440 + \$135,612.9 = \$542,695.25$$

After the total fixed cost is estimated, we can use the discounted year and discounted rate to get the LCOE with and without the fixed cost, which is the structural cost. By using the equation shown below, the result for the LCOE without structure is \$0.166 per kWh and with structure is \$0.286 per kWh.

$$LCOE = Cap\ Cost + NonCap\ Cost$$

$$Cap\ Cost = Annualized\ cost / output$$

$$NonCap\ Cost = 0.004\ per\ watt$$

The LCOE for both conditions is rational because the average electric price in the Miami area is \$0.163/kWh (Average price: Electricity per kilowatt-hour in Miami-Fort Lauderdale-West Palm Beach, FL (CBSA, 2022)). The solar canopy for the basketball court can help the school to save money on utility and put more budget into student education.



Figure 26. Average Cost of Electricity in Miami

Phoenix

Location and Site Analysis

Based on previous market analysis, solar energy has the highest power output efficiency in Phoenix compared to the other three target cities. Combined with the previous climate analysis of Phoenix, the city's average wind speed and solar direct radiation values are relatively high, indicating that the city is suitable for the construction and operation of the solar canopy.

Koppen climate zone:	Arid Desert Hot (BWh)
ASHRAE climate zone:	Hot (2)
Average annual temperature:	23 °C
Annual total solar radiation:	2,079 kWh/m ²
Average annual wind speed:	3 m/s

Figure 27. Climate Data for Phoenix

Since this project aims to build a solar canopy for a basketball court, it is necessary to combine the local population distribution and the possible usage frequency of the basketball court. The basketball court on the south side of Madison Highland Prep was selected as the target court for this project. The basketball court is adjacent to Madison Highland Prep, Madison Park Middle School, and other schools; also, there is a large residential area in the northeast, which ensures the population density around the basketball court and the frequency of use of the court. There are sizable solar canopy parking lots around the stadium, which proves the feasibility of solar canopy construction and operation in the local area.



Figure 28. Madison Highland Prep



Figure 29. Location of the Basketball Court

In order to explore the specific implementation of this project in this area, it is necessary to model this basketball court and apply the solar path map and wind speed map in this area, which can clarify the effect of the solar canopy on direct sunlight in different periods and the impact of wind force to the solar canopy on the stability and safety of building structures. In order to ensure the stability of the solar canopy structure and increase the direct sunlight radiation value of the photovoltaic panels, this project sets the solar canopy tilted at 5 degrees South. This project report uses Rhino 7 to model the basketball court and loads the ClimateStudio plug-in in the software to analyze the climate data of the solar canopy model. Part of the analysis results is shown in the figure below. The solar canopy can effectively block the sun most of the time when the direct solar radiation value is high, and the shaded area provided can effectively cover most of the court area.

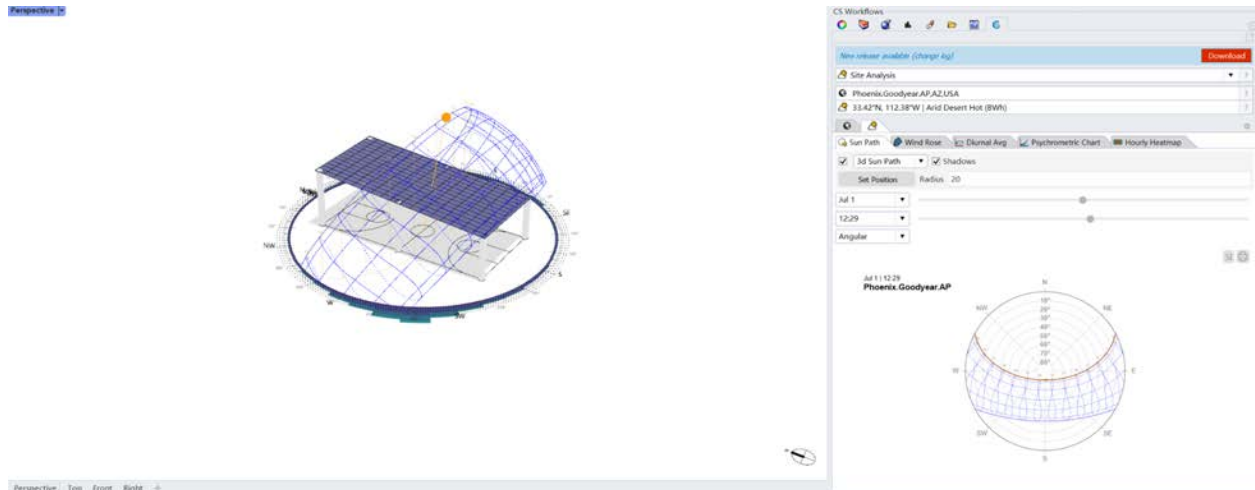


Figure 30. 3D Rendering of the Basketball Court Made Using Rhino 7

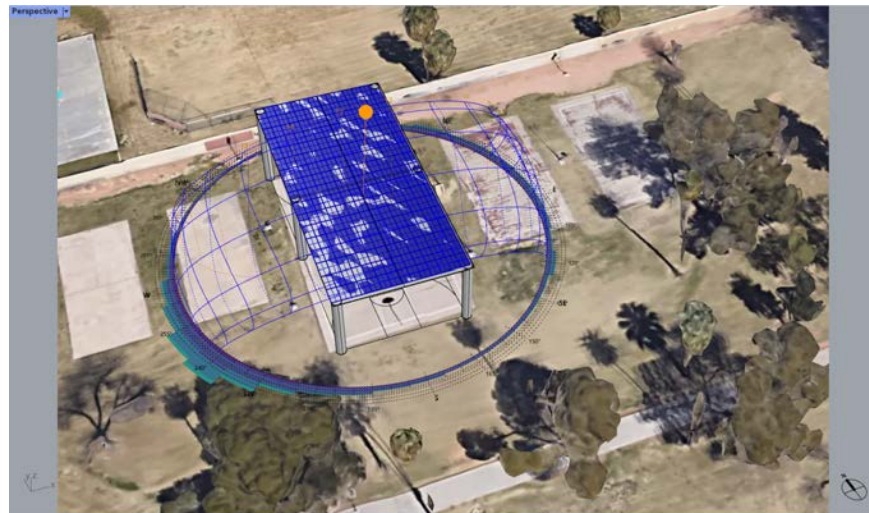


Figure 31. 3D Rendering of Basketball Court After Construction Made Using Rhino 7

In order to make the model more three-dimensional and intuitive, we combined the photos of the court with the model to form a simulated rendering after construction, as shown in the figure above.

Structure and Design

To have more efficiency for solar energy, the design of the roof structure tilts 5 degrees from the origin horizontally.

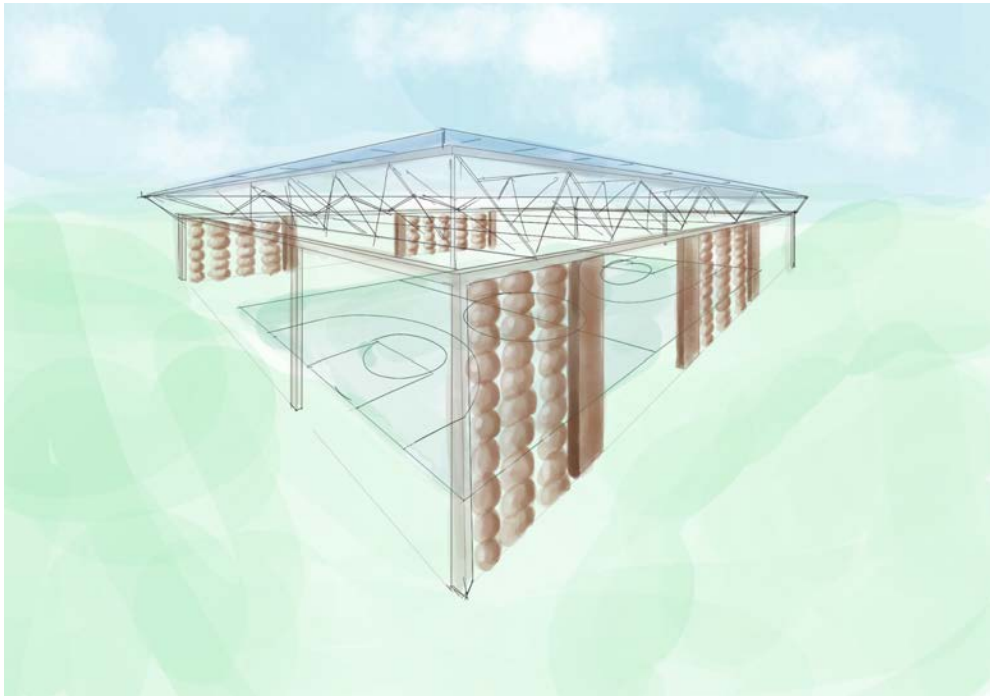


Figure 32. Canopy Structure and Design

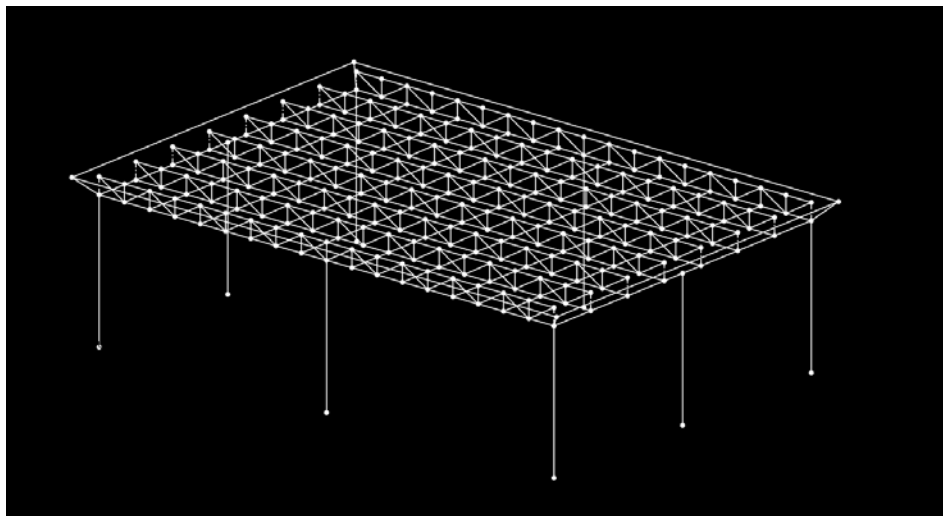


Figure 33. Canopy Structure

The figures above provide schematic drawings of the framework and design of the Phoenix canopy. The canopy will cover one basketball court with a total floor area of 5704 square feet. The roof will carry 288 solar panels to produce solar energy and each solar panel produces 320W.

The breakdown of the structural weight is shown below:

$$\text{HSS } 3 \frac{1}{2} \times 3 \frac{1}{2} \times \frac{1}{8} \text{ Steel Columns: } 200 \text{ linear feet} * 5.61 \text{ lbs/lf} = 1122 \text{ lbs}$$

$$\text{W14 x 22 Steel Beams: } 2412 \text{ linear feet} * 22 \text{ lbs/lf} = 53064 \text{ lbs}$$

$$\text{W10 x 15 Steel Trusses: } 1268.52 \text{ linear feet} * \text{ lbs/lf} = 19027.8 \text{ lbs}$$

$$\text{The Weight of Solar Panels: } 288 \text{ panels} * 40 \text{ lbs} = 11520 \text{ lbs}$$

$$\text{The Weight of the Roof: } 6175 \text{ sqft} * 3 \text{ lbs} = 18525 \text{ lbs}$$

$$\text{Total Weight of the Structure: } 103258.8 \text{ lbs (51.6 Tons *)}$$

** Total Weight of the structure excluding the adobe finishes*

Energy output for the solar system will be 150,646 kWh/Year. With the loss of energy during the transition inside the solar panels, the capacity factor of the solar panels will be 18.65%. If we do not consider the energy loss, the energy output will be 92.16 kW when the solar panels are installed.

$$\text{Energy Output without Energy Loss: } 288 \text{ panels} * 320 \text{ W} = 92.16 \text{ kW}$$

$$\text{Total Annual Production: } 150,646 \text{ kWh}$$

$$\text{Capacity Factor: } 150,646 \text{ kWh} / (92.16 \text{ kW} * 24 \text{ hr} * 365 \text{ days}) = 18.65\%$$

Solar Resource

Phoenix has between 10 and 14.5 daylight hours per day throughout the year. Due to its long sunlight hours, its average annual solar production per kW installed, with the panels tilted at 5 degrees South (angle chosen for the structure), would be 1,635 kWh/kW/yr. If the panels were placed to optimize production, they would be tilted at 33 degrees, about Phoenix's latitude, which would produce 1,782 kWh/kW/yr.

Cost

Before estimating the Levelized cost of electricity (LCOE), we assume a discounted life of 20 years and a discounted rate of 5%. It is necessary to calculate the structure cost because the

structure cost will affect the estimation of LCOE. The total cost of the structure is broken down below:

$$\textit{Total Cost of Steel: } 3880.52 \text{ linear ft} * \$15 = \$58,207.8$$

$$\textit{Total Cost of Solar Panels: } 288 \text{ panels} * \$425 = \$122,414.4$$

$$\textit{Total Cost of Concrete Rehabilitation: } 5704 \text{ sqft} * \$8.25 = \$47,058$$

$$\textit{Total Cost of Roof: } 6175 \text{ sqft} * \$15 = \$92,625$$

$$\textit{Total Cost of Adobe Finishes: } 1155 \text{ sqft} * \$120 = \$138,600$$

$$\textit{Total Cost of Accessories and Equipment: } = \$81,988$$

$$\textit{Total Fixed Cost of the Structure} = \$540,893.2$$

After the total fixed cost is estimated, we can use the discounted year and discounted rate to get the LCOE with and without the fixed cost, which is the structural cost. By using the equation shown below, the result for the LCOE without structure is \$0.155 per kWh and with structure is \$0.261 per kWh.

$$LCOE = Cap\ Cost + NonCap\ Cost$$

$$Cap\ Cost = Annualized\ cost / output$$

$$NonCap\ Cost = 0.004 \text{ per watt}$$

The LCOE for both conditions is rational because the average price of electricity in the Phoenix area has ranged from \$0.137/kWh to \$0.161/kWh (Average price: Electricity per kilowatt-hour in Phoenix-Mesa-Scottsdale, AZ (CBSA, 2022)). The solar canopy for the basketball court can help the school to save money on utility and put more budget into student education.



Figure 34. Average Cost of Electricity in Phoenix

Conclusion

This project designed a solar canopy to cover two basketball courts in Hialeah Miami Lakes Senior High school. This large canopy can fit 765 panels, each rated with a capacity of 200W. The expected total annual production is 227,529 kWh, resulting in a capacity factor of about 17%. The cost of the structure totals \$542,695.25 and the levelized cost of electricity (LCOE) is estimated to be \$0.166/kWh without the structure and \$0.286/kWh with the structure.

The solar canopy designed next to Madison Highland Prep Middle School will only cover one basketball court. This smaller structure can fit 288 panels rated at 320W each totalling an annual production of 150,646 kWh. The resulting capacity factor is 18.65%. This structure, unlike the Miami structure, includes design elements such as adobe finishes and new basketball equipment leading to a total fixed cost of \$540,893.2. The LCOE is estimated to be \$0.155/kWh without the structure and \$0.261/kWh with the structure.

In a direct side by side comparison, it is concluded that the annual production of the Miami canopy is 76,883 kWh greater than that of Phoenix. This is to be expected because the capacity of the roof is 153kW compared to Phoenix's 92.2 kW capacity. Because of Phoenix's greater solar resource, the capacity factor of the phoenix roof is about 1.7% higher than that of Miami. Despite the significant size difference of the two structures, the cost of the Miami structure is only about \$1800 more expensive which is less than a 1% increase in price. This is the result of

the additive design and equipment elements to the fixed cost of the Phoenix roof. Lastly, the LCOE of Phoenix is \$0.011 less than that of Miami when you don't factor in the cost of the structure. Including the structure, the LCOE of the Phoenix structure is \$0.025 less.

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