Solar at the Brooks Family YMCA: An Informed Decision-Making Model

A Technical Report submitted to the Department of Civil Engineering

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

By

Morgan Griffin

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

Spring, 2024

Technical Project Team Members

Lauren Beachy
Hannah Billing
Jack Dressen-Higginbotham
Julia Lombardi
Liam Shields

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Reid Bailey, Department of Systems Engineering

Introduction

Design Problem Statement

For the past few years, the Brooks Family YMCA in Charlottesville, VA has been interested in the possibility of installing solar panels on the roof of their facility. Being a leader in sustainability within their community is at the forefront of their values and was the driver of this interest. When Commonwealth Power approached the YMCA in 2021 about a potential solar project, the YMCA had little knowledge about solar and found it difficult to understand the proposal given to them. They were unable to determine if it was structurally and economically viable for them, causing the YMCA to not accept the proposal. However, the YMCA was still interested in a solar installation project and reached out to UVA for analysis and guidance. The YMCA board is less concerned about the economic benefits of installing solar than about prioritizing the community educational opportunities that result from the project. The main objective of this project was to help the YMCA by conducting an analysis on how solar could fit into their facility and work to meet their goals.

Design Objectives

Identifying the main objectives of a solar project is vital for measuring its success. The YMCA has environmental objectives such as aiming to lessen their carbon footprint through using solar energy and, to a lesser extent, economic objectives such as saving money. Quantitative metrics for environmental objectives include the amount of electricity produced by solar and the percent of traditional electricity offset by this solar production. Quantitative metrics for economic objectives include net present value (NPV) and, if an initial investment is required, return on investment (ROI) and payback period. Identifying objectives beyond environmental and economic ones is important too. For example, objectives could be social, such as setting a community example or providing youth educational opportunities in which the YMCA strives to accomplish. While some metrics were more difficult to quantify, they were still able to be taken into account during the analysis and in making the final recommendation.

In addition to objectives, identifying the constraints within which any solution must operate is critical. The YMCA project was constrained by the structural capacity of the building, size of the roof, the financial investment required, and limitations from federal or local codes. For example, according to the building's lead structural engineer, the building might not have the structural capacity to hold the maximum amount of panels that could fit on the roof area. These objectives and constraints shaped the scope of the project and created a clear vision of our goal.

Our project's success requires providing the YMCA with the information and calculations needed to achieve their goals for a solar project on their building. This means providing the YMCA executive board with a presentation that includes our analysis and decisions regarding system size, financial agreement type, configuration and number of panels and required auxiliary electrical equipment.

Background

While rooftop solar technology emerged in the late 1960s, the solar industry has grown substantially in recent years. The industry is becoming more popular in both the residential and commercial sectors. For a building owner, making an informed decision about solar that integrates economic, environmental, and practical factors is complicated by proposals from different companies that cannot be directly compared. Navigating solar energy in today's society involves making decisions such as selecting a financing option, a mounting type for the solar panels, the system size, and a solar installer. The decisions are made more complex due to varying economic incentives, structural limitations, and objectives of both the solar installers and owners of a building.

Due to the complex, integrated nature of commercial solar projects, taking a holistic approach is crucial, especially as seemingly disconnected factors often affect each other. For example, the placement and weight of solar panels impact not only the electrical production, but also the building structure, cost, maintenance, and lifespan, while local, state, and national policies influence the project's economics. The importance of understanding the underlying systems becomes apparent when comparing different solar company quotes. Each quote, through making different assumptions about how its proposed design interacts with the larger system, takes a more isolated decision approach. In a worst-case scenario, the quotes consider the solar project in isolation from the larger system. The YMCA, for example, had several solar companies unrealistically maximize the number of solar panels that could possibly fit on the roof without considering the structural capacity of the building. Not considering the entire system limits the ability to make an informed decision about the best solar system design for a particular project.

Design

Solar Research

Research on solar power, as well as the current systems in place at the YMCA, was critical to achieving the project objectives. The YMCA's relevant major systems include the electrical system and the current roof structure. The YMCA currently receives its electricity from Dominion Power and used a total of 2,114,560 kWh in 2022. From the electrical bill provided from the YMCA, it was found that the YMCA pays between $0.06 and $0.11 per kWh of electricity depending on the time of year.

Another consideration is ensuring that the roof where the panels would be placed is capable of holding them. From the building plans, the roof is 52,517 square feet and has a design live load of 20 PSF (see Figure 1). The roof has three distinct sections, including two wing sections that are flat roofs, and a middle section that is both flat and inclined. The structural engineer of the building expressed hesitation in installing solar. The engineer is aiding in the analysis of dead load, live load, drift areas, and more to ensure the safety of the building, as well as those involved in installation and maintenance.

1. DESIGN LIVE LOADS		
MECHANICAL EQUIPMENT ROOMS	150	PSF
1ST FLOOR	100	PSF
OFFICES (+20 PARTITION)	70	PSF
PUBLIC ROOMS/LOBBIES	100	PSF
ROOF LOADS: (FLAT ROOFS)	20	PSF
STAIRWAYS	100	PSF
STORAGE ON GRADE (HEAVY)	250	PSF

Figure 1: Design Live Loads from the Structural Construction Plans

Rooftop solar demands minimal maintenance, as the angled position of the panels allows rain to naturally clean the system . In addition, it is recommended to clean the panels two to four times a year by spraying, rinsing, or wiping down the panels using lukewarm water. It is recommended to use water only to clean the panels, as soap can leave streaks that damage the panels and reduce system functionality. Additionally, when cleaning the panels, any dirt, leaves, and other debris should be removed. Another component of maintenance of a solar panel system is to eliminate any shadows that can cast over panels and cause an obstruction of sunlight, such as trimming an overgrown tree. In the occasion of a winter storm, snow and ice usually melts off of panels naturally due to the angled nature of the panels, but if the problem persists, the similar procedure of spraying them with lukewarm water suffices in non-extreme conditions (Gerhardt, 2023). An optional annual inspection with the solar company that installed the system to ensure the panels are working properly is available if desired and the cost per visit varies depending on the solar company. After 25-30 years, the solar system must be replaced due to a loss of solar panel efficiency. Figure 2 describes the installation, maintenance, and lifespan associated with a solar installation. With regards to risk mitigation, each solar electric system is designed with safety as a primary concern. In the event of an emergency, such as an electrical fire or severe weather events, the system includes a fail-safe switch that allows for immediate shutdown. This feature ensures that the system can be quickly and safely deactivated, protecting both the facility and the utility workers who might need to perform maintenance. These safety measures comply with National Electric code 690.4 (D), see appendix C1.

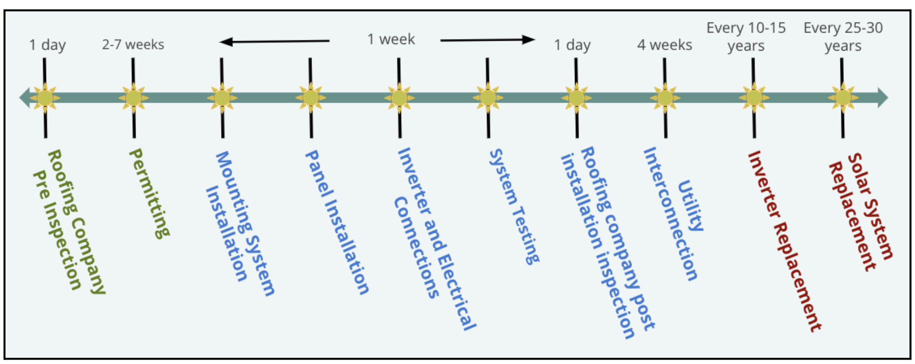


Figure 2: Solar System Lifespan

There are three ways to mount solar panels to commercial roofs. Bonded installation is achieved by welding a rail to the roof. This method adds less weight then other methods; however, it can be more expensive and damage the roof material. A mechanically fixed installation attaches the solar panels directly to the roof. This mounting system has the highest wind resistance, however, it does involve penetrating the roof material, leading to a high risk for leaks and possibly voiding the warranty on the roof if not inspected properly. A ballasted mounting system involves using added weight to hold the panel racking in place. Ballasted systems are not suitable for slanted roofs, but they do not involve any penetrations to the roof material (Nicholson, 2022).

Another major section of research conducted involved the purchasing options for a solar system and the different government incentives currently in place to aid in a solar project. Purchasing options include owning and a power purchase agreement (PPA), seen in Figure 3. In an owned system the business owner purchases the panels upfront and is responsible for all maintenance costs, installation costs, and performance regulation. In a PPA, a third party owns and maintains the solar system installed on the customer's building, with an agreement from the building owner that they will buy power from the system. PPAs charge a fixed rate per kilowatt of energy produced by the system (Mack, 2023).

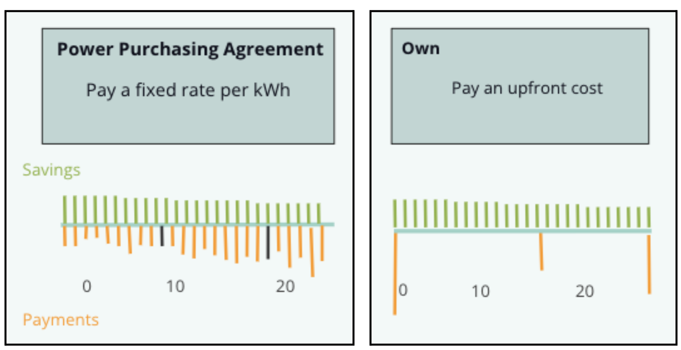


Figure 3: Solar Financing Options

As for government incentives, the Inflation Reduction Act tax credit can provide up to 30% of funding assistance for a solar project throughout 2032. Since the YMCA is considered a nonprofit and does not pay taxes, 30% of the total cost of the system would be paid directly back to them at the end of the first fiscal year in which they buy the system. Additionally, the government could cover up to 50% of the project funding through a REAP grant. The Rural Energy for America Program (REAP) Grant provides financial assistance to rural for-profit small businesses purchasing renewable energy systems (Wolf, 2024). Although Charlottesville is considered a rural area, the YMCA is not considered a small business. However, if they were to decide to do a PPA, the owner of the system who sells power back to the YMCA could be considered a small business and be eligible for the REAP grant. Solar Renewable Energy Certificates (SRECs) are created for each megawatt-hour of electricity generated from solar energy systems (Pivot Energy, 2022). A key economic decision is deciding whether to sell or keep the SREC to reduce a business's carbon footprint, as SRECs serve as the "green" value of a system's electricity. The amount earned from selling SRECs varies by state. Local, state, and federal governments often incentivize solar through other grants and credits as well, which can change year to year and are important to monitor.

Education

Education plays a fundamental role in the YMCA achieving their community goals. The Brooks Family YMCA has multiple educational programs such as the YMCA Early Learning Center, after school programs, and teen programs. Integrating solar panels to the YMCA would establish the community center as a sustainability leader in the Charlottesville community. Installing solar panels and integrating solar education into the YMCA's current educational programs would fulfill the YMCA's mission of providing comprehensive programs and services that enrich communities.

One way to increase the visibility of the system is a renewable energy tracker and monitor system placed in the main entrance at the YMCA. For example, the University of Virginia created a renewable energy tracker that calculates the real-time solar power production across Grounds. Depicted on UVA's website, the user can view the total metric tons of carbon dioxide avoided since using solar power at the University (see Figure 4). This renewable energy tracker serves as just one example of what might be displayed at the YMCA for educational purposes. Educational programs may also be developed to further educate young adults and children on the value of sustainability. By offering a variety of education programs, the YMCA can instill values of sustainability, inspire future generations, and contribute to creating an environmentally conscious community. Additionally, the YMCA's solar installation could educate and inspire similar nonprofits or businesses in the greater Charlottesville area to consider a solar installation, furthering its impact on sustainability in the community.

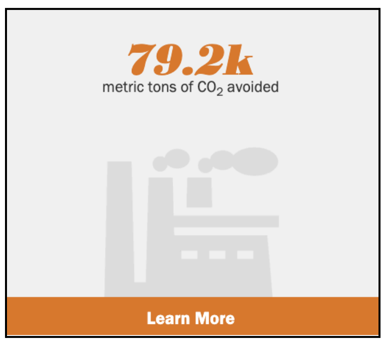


Figure 4: UVA's Renewable Energy Tracker Display

Solar Company Proposals

Four solar companies were selected to create proposals for the YMCA. Satish Anabathula, the Director of Power and Light at UVA and Ethan Heil, this capstone project's assigned professional engineer highlighted the most relevant and reputable companies known in the Charlottesville area to reach out to. The four companies interested in conducting a solar project at the YMCA are Convert Solar, Suntribe Solar, Sunday Solar, and Tiger Solar (see Figure 5). Convert Solar is a residential and commercial solar energy provider with 12 years of experience of installations across Coastal Virginia. Suntribe Solar is a commercial-scale solar provider founded in 2016 with over 100 projects completed in the surrounding areas. Sunday Solar is a Charlottesville based firm founded in 2010 that has installed 3129 kW of solar. Tiger Solar is backed by Tiger Fuel, with 18 years of experience, building solar arrays frequently over 100 kW and operating all in house.

Figure 5: Selected Solar Companies

Proposal Comparisons

Each company proposed a different design for the solar array, with sizes ranging from 642 panels to 815. The proposals were either PPAs or owned systems that ranged in price from $787,000 to $1.1 million before incentives. National Electric Code requires the racking equipment's UL listing to meet the required specifications of UL 703. The proposals listed the racking brand and UL listing, which we ensured met the requirements. Looking at the tilt listed in each proposal, we verified it met the requirements listed in Sec 34-1108 of the City of Charlottesville solar ordinance, not surpassing a height of 5 ft above the highest point of the roof. For more standard and code verifications, see Appendix C1, C2, and C3. Tiger Solar was the only company to perform a site visit of the YMCA, and it was determined their proposal most accurately considered the structural limitations found. Each company proposed different combinations of sections of the roof to be utilized for the solar panels. Convert Solar, Sunday Solar, and Suntribe proposed using almost the entire roof, as pictured in configuration A in Figure 6. Tiger Solar proposed using all sections of the roof besides the middle section (covering the gym and pool section), as pictured in configuration B. However, the original lead structural engineer of the YMCA suggested that configuration C would be most structurally ideal, warning that the building may not perform as it was designed to with a solar array covering the whole roof (configuration A).

Figure 6: Proposed Roof Configurations A, B, and C

Due to the varying presentation of information within the four models, Table 1 was made to help compare the decisions each company had made. Decisions such as cost before and after incentives, number of panels, system size, number and size of inverters, usage offset, and panel degradation rates were used to compare each proposal to one another. The Suntribe proposal lacked significant information, and was therefore difficult to assess properly as seen in the table below. Additionally, Convert Solar proposed the full amount of the solar installation although this cost would be taken by a third party whom the YMCA would be buying energy from in a PPA agreement (their upfront payment would be $0).

	Tiger Solar	**Sunday Solar**	**Convert Solar**	**Suntribe Solar**
Proposal Type	Own	Own	PPA (through LLC)	PPA
Total Cost Before Incentives	$721,500	$1,081,913	$1,126,976	$1/yr

Total Cost After Incentives	$505,050	$757,339	$726,109	$1/yr
# of Panels	613	815	807	N/A
System Size	337.15 kW	480.05 kW	459.99 kW	425 kW
Type of Panels/Brand	Axitec 550 W Modules	Q Peak DUO XL-G11.3 590W	Hanwha Q Cells Q PEAK DUO XL-G11.2 570W	N/A
# and Size of Inverters	5 Inverters, 50 kW each	7 inverters	4 inverters (3 SolarEdge SE100kUS, 1 SolarEdge SE80KUS)	N/A
Mounting Type	Ballasted	Ballasted	N/A	N/A
Usage Offset	19%	28%	29.3%	28%
Panel Degradation Rates	0.55%	0.35%	0.70%	N/A
Warranty Info	Panels: 25 yrs Inverters: 10 yrs Installation: 1 yr	Panels: 25 yrs Inverters: 25 yrs Racking: 25 yrs	N/A	N/A
Roof Configuration				

Table 1: Proposal Comparisons

It is important to note that all proposals used solar panels made in China. This was a concern for the YMCA as they wanted to ensure that the products would be ethically sourced. When this was mentioned to Tiger solar, they explained that American made panels would significantly increase price and that they try their best to make sure the companies they buy from source their materials ethically and pay their workers fairly. However, this is not a guarantee as tracing supply lines can be difficult at times. This was a small, but important, consideration for the project and we provided the YMCA with this information for them to be able to make their own decision.

Need for Models

The proposals from the different companies were difficult to compare to each other and validate. Information would be included on one proposal, but not the others. Proposals would have similar designs, but different resulting numbers, or they would have significantly different designs but similar resulting numbers. For example, Sunday Solar proposed a system size of 480.85 kW and Suntribe Solar proposed a system size of 425 kW, but they both reported an electricity offset value of 28%. System size represents the amount of electricity that a solar system produces. With different system sizes, they should be producing different amounts of electricity, and should also have different offset percentages. These discrepancies made it difficult to properly compare the proposals to one another, and brought up the question of how valid each proposal was. The comparison difficulties and concern for the structural capacity drove the need for a more standardized approach. The following sections break down the function of these models and make recommendations based on their results.

Electricity Model

The electricity production model (see Appendix D & Figure 7) is a tool to evaluate the energy output from added solar. It integrates key assumptions and parameters derived from industry standards, manufacturer specifications, empirical data, location, and design of the building. Assumptions include average panel size (sqft), roof-to-panel coverage ratio (%), annual degradation rate, panel efficiency (%), and panel capacity (kW). Normalizing these factors provides a standardized framework for evaluating the electrical production of solar projects independent of individual proposals. Coverage ratio is the percentage of the roof area that is suitable for solar. Articles 605.11.3.2.1 and 605.11.3.2.4 of International Fire Code require a 3ft clearance from the ridge of a pitched roof, both across the ridge of the roof and down along the side of the roof (see Appendix C1 for more). The coverage ratio included in the model was determined as an industry standard that includes these placement codes. The location specific parameter was peak sunlight hours for Charlottesville, VA. Building specific parameters include total roof area and number of unique roofs. The model uses these assumptions and parameters to calculate the total usable roof area, maximum number of panels, system size (kW), and percent offset. It then produces adjusted electricity production estimates for a 25 year period, accounting for panel degradation.

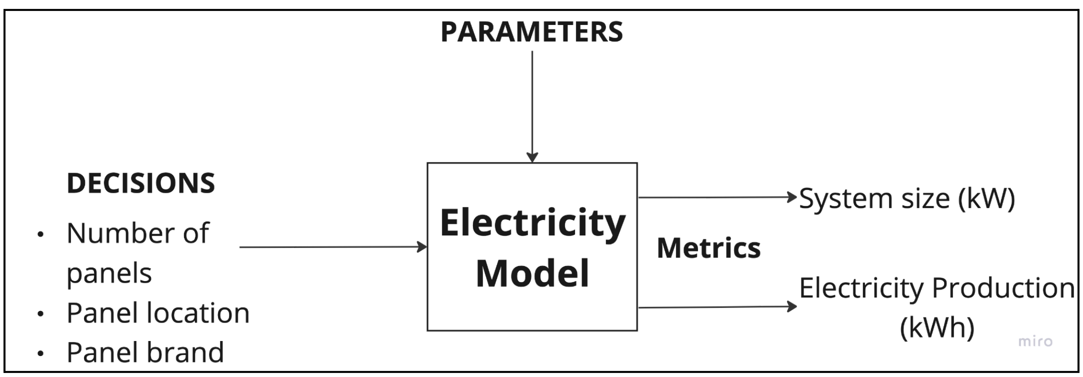


Figure 7: Electricity Production Model Outline

Location and Building Specific Parameters:

- H_{peak}: Average daily hours of peak sunlight (kWh/m^2/day)
  - 4.5 hours/day in Charlottesville
- S_l: Total square footage of roof l (m^2)
  - 44,712 sqft for the building

Table 2 shows the differences between proposal and model numbers for 5 metrics. For the "model" numbers the system size, number of panels, percent offset, and electricity production are calculated by the model, whereas panel capacity is averaged based on quote estimates. The "model" system size is used in the following economic model to estimate initial system cost.

Co.		Electricity Model Outputs Compared to Proposal Outputs				
		System Size (kW)	***# of Panels***	***% Offset***	***Panel Cap. (W)***	***Elec. Prod. (kWh)***
1	Sunday	480.85	815	28	570-590	607,300
	Model	487.6	841	27.9	580	596,212
2	Suntribe	425	N/A	28	N/A	582,420
	Model	429.4	795	26.4	540	563,984
3	Convert	459.9	807	29.3	570	636,651
	Model	466.3	818	29.6	570	624,097
4	Tiger	337.2	613	19	530-555	415,221
	Model	331.3	613	20.4	540	435,074

Table 2: Electricity Model Outputs Compared to Proposal Outputs

Economic Model

Economically, two important decisions must be made: choosing the appropriate financial agreement and identifying local, state, and federal programs that could help fund the installation. The economic model (see Appendix D & Figure 8) provides a comprehensive financial analysis of the two most common solar financial agreements: owned and PPA. This integrates assumptions and parameters grounded in the economic realities of solar investments and energy markets. Assumptions include system price per watt, utility escalation rate, SREC price, annual maintenance cost, inverter replacement cost and frequency, PPA price and escalation rate, and system lifespan. Assumptions such as the PPA price, utility escalation rate, and maintenance costs, will vary based on specific project locations, market conditions, and contractual terms. It is essential to normalize and customize assumptions to accurately assess potential return of solar projects in different environments and situations.

Specific parameters based on the current electrical production include the initial grid electricity cost ($/kWh), the annual utility bill, annual energy usage (kWh). From the Electricity Production Model, parameters include the System Size (kW) and the predicted total electricity production post-solar (kWh). The economic model produces metrics such as the expected initial system cost, yearly maintenance cost, annual electricity savings, inverter replacement cost, offset percent, and SREC revenue. For an owned system, the net present value (NPV), upfront cost, and payback period are calculated. For PPAs, it evaluates the financial impact of buying electricity at a predetermined rate over the agreement term by calculating NPV. Using both the electricity production and economic model will allow a business to normalize assumptions and parameters given by solar proposals to determine if it is economically viable to implement the installation of a solar rooftop on a commercial building. For the YMCA, we used the electric and economic models with two different configurations (see Figure 9) to determine which configuration and system size resulted in the most desirable outcome (see Table 3).

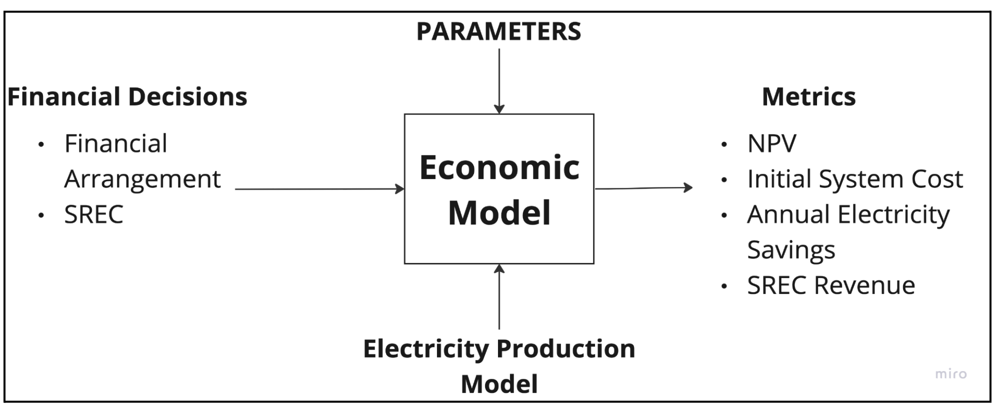


Figure 8: Economic Model Outline

Project specific parameters:

- U_i: Annual utility bill in year i
  - $145,345 for year 1
- $E_{usage,\ i}$: Total annual energy usage in year i (kWh/year)

- ○ 2,137,547 kWh/year for year 1
- P_i: Utility electricity rate in year i, adjusted for the utility escalation rate
  - ○ $0.07 for year 1

The model considers two configurations on the roof:

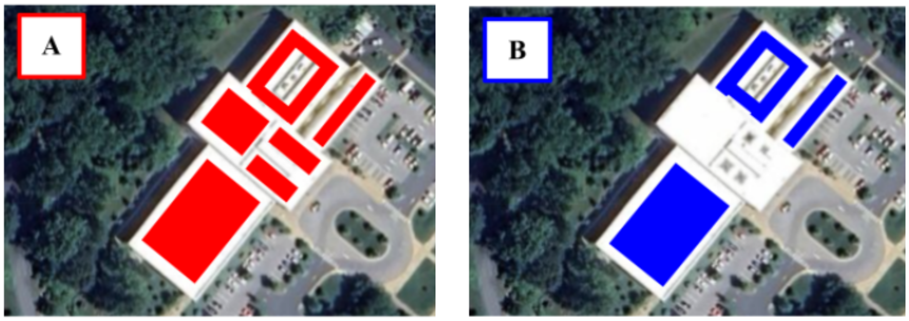


Figure 9: Solar Panel Configurations Considered by the Economic Model

	Economic Model Outputs Compared to Proposal Outputs					
			Proposal		***Model***	
	Finance Plan	***Proposal***	***NPV ($)***	***Payback Period***	***NPV ($)***	***Payback Period***
A	Owned PPA PPA	Sunday Suntribe Convert	197k -145k N/A	17 years N/A N/A	202k -150k -200k	16 years N/A N/A
B	Owned	Tiger	194k	18 years	198k	16 years

Table 3: Economic Model Outputs Compared to Proposal Outputs

It is important to note the proposal NPVs were calculated by the authors as some quotes only provided cash flows. Comparing NPVs rather than cash flows is important as the project continues to cost or earn (depending on financial agreement type) a significant amount of money each year over its lifespan of 25 years. These continuing costs and earnings can more accurately be assessed by using NPV and can help the YMCA better understand the value of the project rather than just the cash flows. The higher NPV from our model is mostly attributed to the incorporation of SREC sales, which were not included or were only partially considered in the quotes. PPAs in this market, location, and array size are not a good investment as they result in a negative NPV. The PPA is not economically viable in this market due to the high price per kWh in comparison to the current electricity provider and extremely high interest rates make PPAs much less attractive. Owned models show a positive NPV over the 25 years and configuration "A, owned" yields the best economic results.

Any of these configurations can satisfy the main educational objective, because in all cases, they would have solar panels that would be seen by the community. Even the PPAs, where they are losing money, would satisfy this objective. The owned systems, specifically Option A, allows them to satisfy all their objectives, economic and educational. However, the structural limitations of the building put the feasibility of configuration A at risk. This makes configuration "B, owned" the optimal choice for fulfilling all objectives. The inputs and results show the complexities of real situations and how considering a holistic range of measures and objectives, comparing alternative designs, and using shared assumptions can help companies make more-informed decisions.

Recommendation

After using the economic model and speaking with professional engineers experienced in the solar industry, we recommend the YMCA adopt the "own" financial agreement type. After using the electricity production model and consulting the structural engineer of the Brooks Family YMCA building, we recommend the YMCA have a system size of about 330kW, with 613 panels that each have a capacity of 540 W, 7 inverters, and the panels be placed in configuration B (see Table 4).

Decisions	Recommendation
Financial Agreement Type	Own
System Size	330 kW
Number of Panels	613, 540 W each
Number of Inverters	7
Configuration	

Table 4: Final Recommendation to the YMCA

Discussion

While the main focus and objective of the project was to aid the Brooks Family YMCA in making a decision about a solar installation, our electricity production and economic model can be applied to any commercial business or nonprofit building. With the model's user-friendly chronological steps and instructions, any facilities director, manager, or individual interested can input their building's data in order to see if solar is a viable decision. This applicability to more than the YMCA makes this project useful for years and multiple projects to come. Current free solar calculators on the market lack a focus on the interrelationships between metrics, decisions, and objectives unique to a company aiming to make an informed decision on commercial solar installation. Limitations of the project include that the model relies upon the estimation of several time dependent market assumptions and parameters such as price per kW of power and coverage ratio. If these assumptions are inaccurate, they make the model inaccurate. Additionally, the economic model does not investigate the leasing purchasing option and does not account for economies of scale. These factors mean the model can be extremely variable depending on the year it's used, the accuracy of the assumptions, and the decisions prioritized.

Conclusion

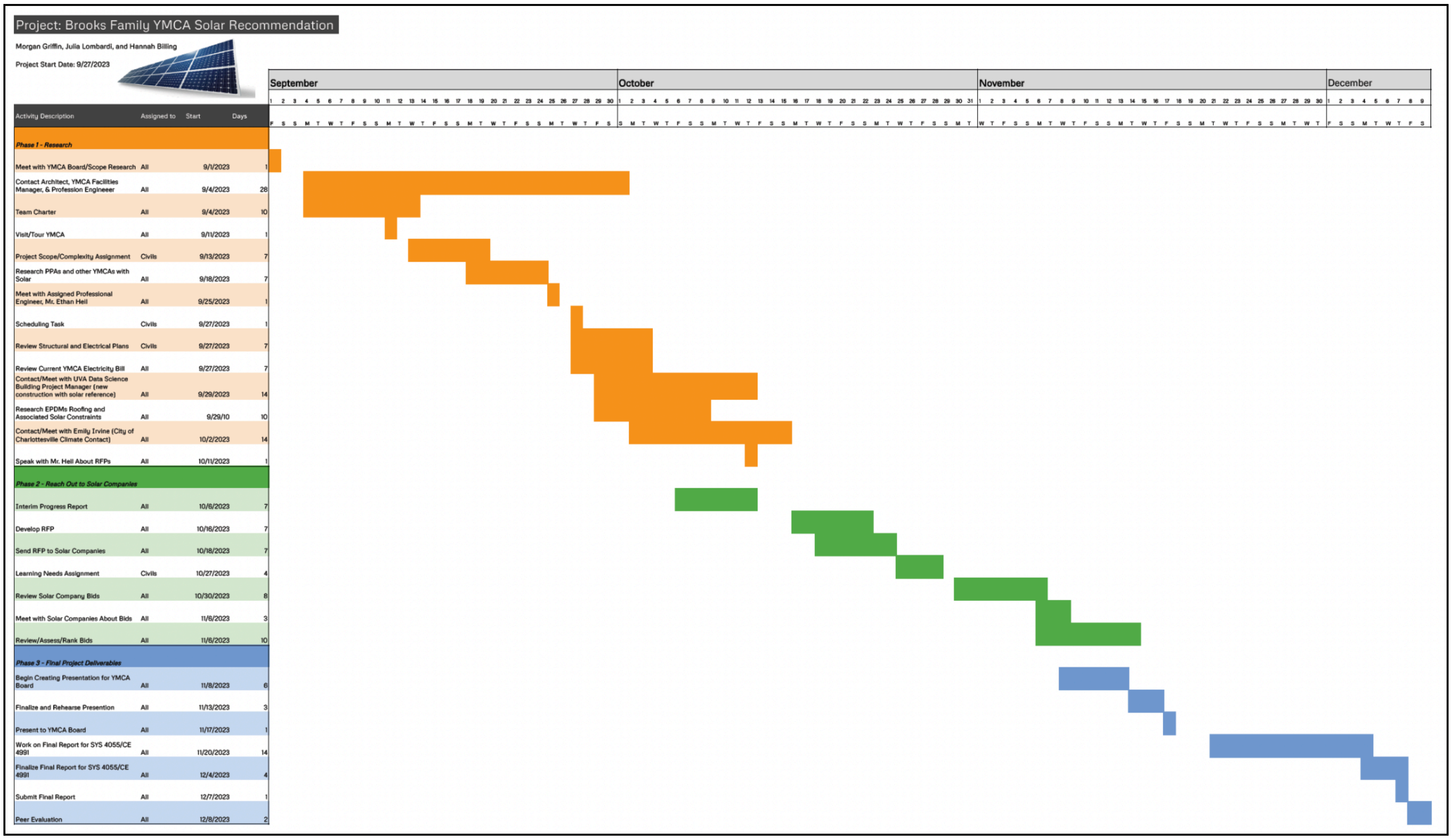
The objective of the project was to evaluate the viability of installing solar panels on the roof of the local YMCA. This involved communicating with the YMCA and speaking with professional engineers in the solar industry to set objectives along with receiving quotes from solar companies and contacting a structural engineer to understand limitations. The model provides the YMCA the recommended system size, respective financial agreement NPV and payback period, configuration and number of panels, and required number of inverters. By using location-specific and building-specific parameters, our electricity production and economic models offer a more personalized experience in comparison to other models. This allows the user to prioritize certain decisions and metrics of success over others. While we are confident in our models, it is important to consider these values estimations. There are limitations in the model, and it is meant as a tool to make a more informed decision.

Appendices

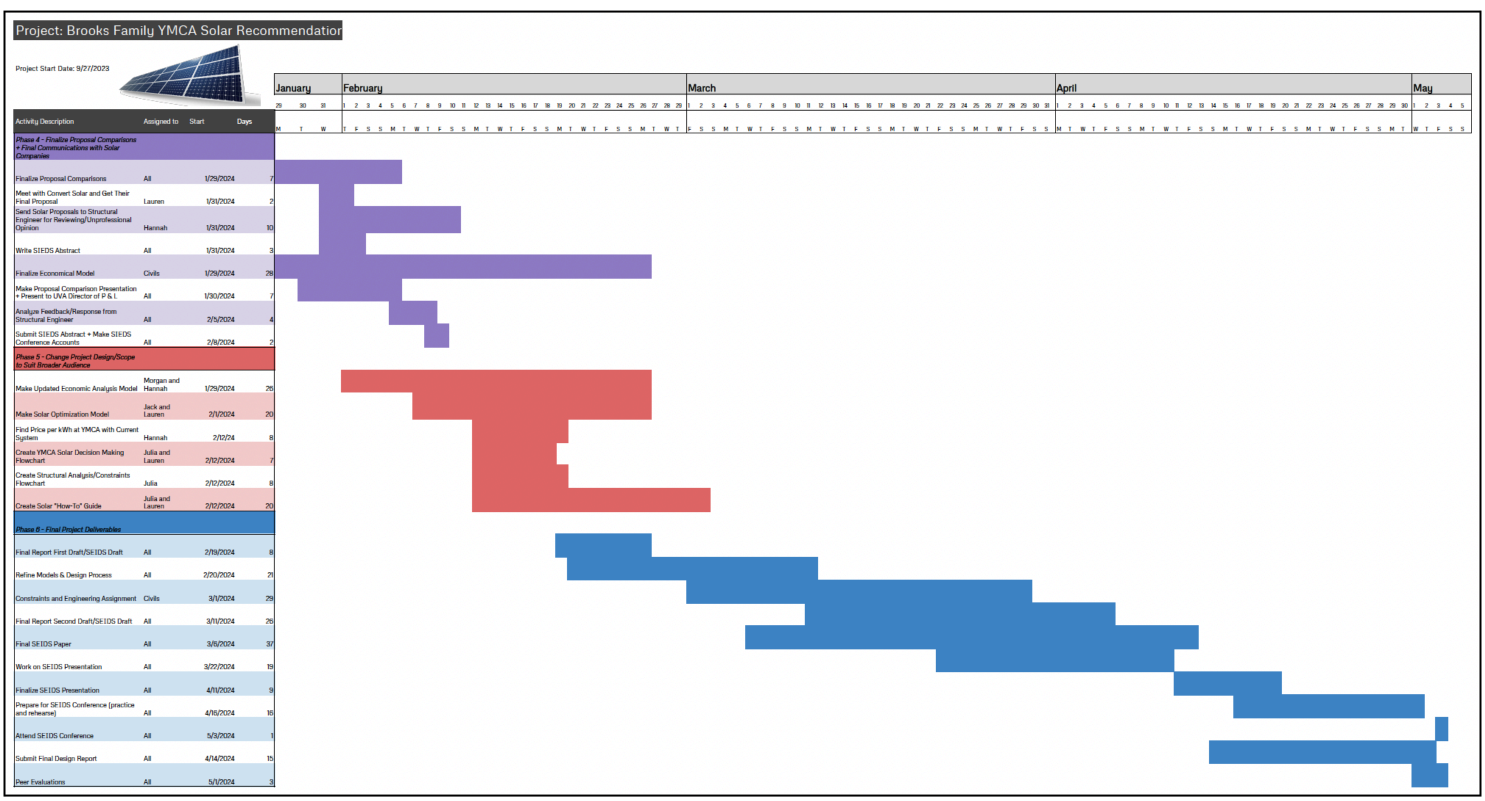
Appendix A: Detailed Schedule

Capstone Schedule Gantt Chart

Semester 1:



Semester 2:



Appendix B: Design Evolution

The YMCA requested that the team evaluate the feasibility of installing solar panels on their building in Charlottesville. Initially, we planned to analyze the proposals from the different companies, and give a detailed recommendation to the YMCA. The recommendation would include which proposal to choose, the optimal layout of the panels, and the economic implications. The structural engineer for the YMCA building was hesitant to add panels to the roof, unsure if the building would perform how it was designed, under the additional loads.

The proposals we received from the different companies were difficult to compare and validate. Information would be included on one proposal, but not the others. Proposals would have similar designs, but different resulting numbers, or they would have significantly different designs but similar resulting numbers. These discrepancies made it difficult to properly compare the proposals to one another, and brought up the question of how valid each proposal was.

The comparison difficulties and concern for the structural capacity caused a shift in the design of the project. Instead of focusing on giving a detailed recommendation based on the proposals, we created a model that the YMCA could use to help them compare the different proposals in order to make an informed decision. The first model we created only considered the economics of the proposal. The model calculated the net present value, IRR, and cumulative cash flow. We created this model based on the averages of each of the proposals that we received. The model only calculated these metrics for an owned system.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**Assumptions:**			**Changable Variables**			**System Size Inputs:**			**YMCA Specific:**			
2	Price per kW:	$ 2,250.00		System Size (kW):	142		Roof Size (ft^2)	52517.12		Pool Roof (ft^2)	19816		
3	Panels Degregation Factor	0.35%					Number of Panels	3501		Middle Roof (ft^2)	10344.1		
4	SREC price per kW	$ 0.04		**Calculations**			System Size:	**722**		Gym Roof (ft^2)	9278.49		
5	Utility Escalation	3.00%		Offset Percent	#DIV/0!					School Roof (ft^2)	5274.32		
6	Annual Energy Consuption (kWh)			Energy Pre-Solar (kW)						Total Available Roof	44712.91		
7	Annual Utility Bill			Solar production (kW/yr)	169496.1								
8	Production rate	1,245.9647466		NPV:	$ 123,894.27					**System Size Inputs:**			
9	Insurance rate per kW	$ 5.62								Roof Size (ft^2)	44712.91		
10										Number of Panels	2981		
11	With SREC									System Size:	**615**		
12	Year	System Cost	Federal Direct Pay	Annual Insurance	SREC	kW production	kW price	Avoided kW Bills	Annual Cash Flow	Cumulative Cashflow	Net Present Value of Cash Flow	Net Present Value of Cumulative Cashflow	IRR
13	0	$ (319,500.18)							$ (319,500.18)	$ (319,500.18)	$ (319,500.18)	$ (319,500.18)	8%
14	1		$ 95,850.05	$ (798.70)	$ 7,077.08	176927.0	$0.070	$ 12,384.89	$ 114,513.33	$ (204,986.85)	$ 110,640.89	$ (208,859.28)	
15	2			$ (798.70)	$ 7,052.31	176307.7	$0.072	$ 12,711.79	$ 18,965.40	$ (186,021.45)	$ 17,704.41	$ (191,154.88)	
16	3			$ (798.70)	$ 7,027.54	175688.5	$0.074	$ 13,047.16	$ 19,276.00	$ (166,745.45)	$ 17,385.85	$ (173,769.03)	
17	4			$ (798.70)	$ 7,002.77	175069.3	$0.076	$ 13,391.20	$ 19,595.28	$ (147,150.17)	$ 17,076.15	$ (156,692.88)	
18	5			$ (798.70)	$ 6,978.00	174450.0	$0.079	$ 13,744.15	$ 19,923.46	$ (127,226.72)	$ 16,775.02	$ (139,917.86)	
19	6			$ (798.70)		173830.8	$0.081	$ 14,106.23	$ 13,307.53	$ (113,919.19)	$ 10,825.68	$ (129,092.18)	
20	7			$ (798.70)	$ 6,928.46	173211.5	$0.084	$ 14,477.65	$ 20,607.42	$ (93,311.77)	$ 16,197.24	$ (112,894.93)	
21	8			$ (798.70)	$ 6,903.69	172592.3	$0.086	$ 14,858.67	$ 20,963.67	$ (72,348.10)	$ 15,920.05	$ (96,974.88)	
22	9			$ (798.70)	$ 6,878.92	171973.0	$0.089	$ 15,249.52	$ 21,329.75	$ (51,018.36)	$ 15,650.30	$ (81,324.59)	
23	10			$ (798.70)	$ 6,854.15	171353.8	$0.091	$ 15,650.45	$ 21,705.90	$ (29,312.45)	$ 15,387.72	$ (65,936.87)	
24	11			$ (798.70)	$ 6,829.38	170734.5	$0.094	$ 16,061.71	$ 22,092.39	$ (7,220.06)	$ 15,132.09	$ (50,804.78)	
25	12			$ (798.70)		170115.3	$0.097	$ 16,483.56	$ 15,684.86	$ 8,464.80	$ 10,379.98	$ (40,424.80)	
26	13			$ (798.70)	$ 6,779.84	169496.1	$0.100	$ 16,916.26	$ 22,897.41	$ 31,362.20	$ 14,640.70	$ (25,784.10)	
27	14			$ (798.70)	$ 6,755.07	168876.8	$0.103	$ 17,360.09	$ 23,316.47	$ 54,678.67	$ 14,404.49	$ (11,379.61)	
28	15			$ (798.70)	$ 6,730.30	168257.6	$0.106	$ 17,815.33	$ 23,746.93	$ 78,425.60	$ 14,174.32	$ 2,794.71	
29	16			$ (798.70)	$ 6,705.53	167638.3	$0.109	$ 18,282.25	$ 24,189.09	$ 102,614.69	$ 13,949.99	$ 16,744.70	
30	17			$ (798.70)	$ 6,680.76	167019.1	$0.112	$ 18,761.16	$ 24,643.23	$ 127,257.92	$ 13,731.30	$ 30,476.00	
31	18			$ (798.70)		166399.8	$0.116	$ 19,252.35	$ 18,453.65	$ 145,711.57	$ 9,934.73	$ 40,410.73	
32	19			$ (798.70)	$ 6,631.22	165780.6	$0.119	$ 19,756.13	$ 25,588.65	$ 171,300.23	$ 13,310.08	$ 53,720.81	
33	20			$ (798.70)	$ 6,606.45	165161.3	$0.123	$ 20,272.80	$ 26,080.56	$ 197,380.78	$ 13,107.20	$ 66,828.01	
34	21			$ (798.70)	$ 6,581.68	164542.1	$0.126	$ 20,802.69	$ 26,585.68	$ 223,966.47	$ 12,909.23	$ 79,737.24	
35	22			$ (798.70)	$ 6,556.91	163922.9	$0.130	$ 21,346.14	$ 27,104.35	$ 251,070.82	$ 12,716.02	$ 92,453.27	
36	23			$ (798.70)	$ 6,532.14	163303.6	$0.134	$ 21,903.46	$ 27,636.91	$ 278,707.73	$ 12,527.41	$ 104,980.68	
37	24			$ (798.70)		162684.4	$0.138	$ 22,475.02	$ 21,676.32	$ 300,384.05	$ 9,493.30	$ 114,473.98	
38	25			$ (798.70)		162065.1	$0.142	$ 23,061.15	$ 22,262.46	$ 322,646.51	$ 9,420.29	$ 123,894.27	
39	Total:	$ (319,500.18)		$ (19,967.42)	$ 136,092.24	4237401.5		$ 430,171.80	$ 322,646.51	$ 322,646.51	$ 123,894.27	$ 123,894.27	
40													

Figure 10: First Iteration of Economic Model

The second iteration of the model consisted of two separate models that addressed the limitations of the first model, while producing more metrics. The first part is the electricity model that includes assumptions based on industry standards, instead of the average of the proposals, as we had previously. The electric model takes the peak sunlight hours and usable roof area to produce the yearly electric production from the panels. The usable roof area is calculated based on the total roof area and coverage ratio. The coverage ratio is an industry standard that includes additional clearance for international construction requirements.

Electricity Production Model

Parameters

1

Based on Location

Peak Sunlight Hours (kWh/m^2/day):	4.5

This is the the average number of hours per day that the sunlight is strong enough for solar panels to operate at their maximum capacity.

2

Based on Building

Coverage Ratio:	50.00%

installing solar panels, considering obstructions and spacing requirements.

Roofs:	Roof 1	Roof 2	Roof 3	Roof 4
Roof area(s) (sqft):	20000	0	9000	0
Usable Roof Area (sqft):	10000	0	4500	0
Total Roof Area (sqft):	29000			
Total Usable Roof Area (sqft):	14500			

Enter the total area of each roof section in square feet. The model will calculate the usable space for solar panels based on the coverage ratio. If you have the exact number of panels that can be used, move to step 3.

3

Panels

Panel Size (sqft):	26.40625
# of Panels:	549
Panel Capacity (W):	500
Panel Degredation Rate (%):	0.50%
Panel Efficiency (%):	20.00%

Input the panel capacity in kW if different from the default. The model uses fixed panel size, degradation rate, and efficiency values to calculate the required number of panels based on available roof area unless you specify the number directly. **If you have the number of panels, physically enter it into D20.**

4

System Size

System Size (kW)	274.5

The total capacity of the solar array, which represents the combined power output capability of all installed panels.

5

Production

Annual Energy Usage (kWh):	2137547
Pre Degredation Electricity Production (kWh):	360478.04
% Offset:	16.86%

Enter your Annual Energy Usage (kWh). This will be used to calculate the system's Electricity Production and the % Offset, which indicates how much of your energy needs can be met by the solar system annually.

Yearly Adjusted Electricity Production (kWh)

Year	Adjusted Production (kWh)
1	360478.0
2	358675.6
3	356882.3
4	355097.9
5	353322.4
6	351555.8
7	349798.0
8	348049.0
9	346308.7
10	344577.2
11	342854.3
12	341140.0
13	339434.3
14	337737.2
15	336048.5
16	334368.2
17	332696.4
18	331032.9
19	329377.8
20	327730.9
21	326092.2
22	324461.7
23	322839.4
24	321225.2
25	319619.1

Figure 11: Electricity Production Model

The second part is the economic model. This model takes the electricity production from the first part and uses that, the pre-solar utility cost, presolar electricity use, and price of electricity to calculate the economic implications. This includes; initial system cost, yearly maintenance cost, annual electricity savings, number of inverters, inverter replacement costs, offset percentage, and SREC revenue. The updated model has key outputs that can be used as metrics to measure the success of the project. The assumptions were not built from the proposals as they were previously, instead they are determined from industry standards.

Economic Model

Parameters

#	Parameter	Value	Notes
1	**Based on Electricity Production Model**		These parameters, calculted by the electricity model, are utilized to assess the financial viability and projected savings of the solar system over its operational lifespan
	System Size (kW):	274.5	
	% Offset:	16.86%	
	Pre Degredation Electricity Production (kWh):	360478.04	
2	**Based on System Size**		The Number of Inverters and individual Inverter Cost are predefined; these costs are included in the total system cost. The Inverter Replacement Cost is factored every 10 years, when it may need to be replaced, to accurately reflect this expense in financial calculations.
	Number of Inverters:	3	
	Inverter Cost (each):	$7,000.00	
	Inverter Replacement Cost:	$21,000.00	
3	**Operational Costs**		**Enter your Pre-solar Annual Utility Bill and Annual Energy Usage** to help gauge potential savings. The Yearly Maintenance Cost is estimated based on findings from the National Renerable Energy Labratory (NREL).
	Yearly Maintenance Cost (per kW):	$31.00	
	Pre-solar Annual Utility Bill:	$145,345.00	
	Annual Energy Usage (kWh):	2137547	
4	**Financial Analysis**		**Enter the Initial Grid Electricity Cost if known**; otherwise, it will be based on standard estimates. Utility Escalation Rate, Discount Rate, and Price-Per-Watt (PPW) are predetermined based on industry estimates.
	Initial Grid Electricity Cost ($/kWh):	0.07	
	Utility Escalation Rate:	3.00%	
	Discount Rate:	3.50%	
	PPW ($/W):	2.25	
	PPA Specific		If available from received proposals, enter PPA rates and escalation details; otherwise, these will be estimated to evaluate the PPA's financial impact.
	PPA Rate with Escalation:	0.0848	
	PPA Rate without Escalation:	0.1108	
	PPA Escalation Rate:	3.00%	
	Inital System Cost:	$617,625.00	Initial System Cost is determined by the proposed system size and PPW. The System Cost with ITC includes the 30% federal solar tax credit.
	System Cost with Income Tax Credit (ITC):	$432,337.50	
5	**SREC**		SREC Price is set based on local estimates, and selling SRECs is optional. SREC Revenue depends on whether you choose to sell these credits.
	SREC Price	$50.00	
	SREC Revenue	$18,023.90	
6	**Net Present Value**		The model calculates three NPVs to evaluate the solar project's financial performance under different scenarios, providing a comprehensive financial assessment over the system's lifecycle
	NPV Owned System	$ 236,537.25	
	NPV PPA Without Escalation	$ (67,817.97)	
	NPV PPA With Escalation	$ (99,407.64)	
7	**Return on Investment**		
	ROI Owned System	54.71%	

Owned System Yearly Breakdown

Year	System Cost	ITC (30%)	Annual Maintenance	Inverter Replacement Cost	SREC Revenue	kWh Production	kWh Price	Electricity Savings	Net Savings	Cumm Net Savings	NPV
0	$ (617,625.00)								$ (617,625.00)	$ (617,625.00)	####
1		$ 185,287.50	$ (8,509.50)	$ -	$18,023.90	360478.04	$0.07	$ 25,233.46	$ 220,035.36	$ (397,589.64)	####
2			$ (8,509.50)	$ -	$17,933.78	358675.64	$0.074	$ 26,636.33	$ 36,060.61	$ (361,529.02)	####
3			$ (8,509.50)	$ -	$17,844.11	356882.27	$0.076	$ 27,298.24	$ 36,632.86	$ (324,896.17)	####
4			$ (8,509.50)	$ -	$17,754.89	355097.86	$0.079	$ 27,976.60	$ 37,222.00	$ (287,674.17)	####
5			$ (8,509.50)	$ -	$17,666.12	353322.37	$0.081	$ 28,671.82	$ 37,828.44	$ (249,845.73)	####
6			$ (8,509.50)	$ -	$17,577.79	351555.75	$0.084	$ 29,384.32	$ 38,452.60	$ (211,393.13)	####
7			$ (8,509.50)	$ -	$17,489.90	349797.98	$0.086	$ 30,114.52	$ 39,094.92	$ (172,298.21)	####
8			$ (8,509.50)	$ -	$17,402.45	348048.99	$0.089	$ 30,862.86	$ 39,755.81	$ (132,542.40)	####
9			$ (8,509.50)	$ -	$17,315.44	346308.74	$0.091	$ 31,629.81	$ 40,435.74	$ (92,106.66)	####
10			$ (8,509.50)	$ (21,000.00)	$17,228.86	344577.20	$0.094	$ 32,415.81	$ 20,135.17	$ (71,971.49)	####
11			$ (8,509.50)	$ -	$17,142.72	342854.31	$0.097	$ 33,221.34	$ 41,854.55	$ (30,116.94)	####
12			$ (8,509.50)	$ -	$17,057.00	341140.04	$0.100	$ 34,046.89	$ 42,594.39	$ 12,477.45	####
13			$ (8,509.50)	$ -	$16,971.72	339434.34	$0.103	$ 34,892.95	$ 43,355.17	$ 55,832.62	####
14			$ (8,509.50)	$ -	$16,886.86	337737.17	$0.106	$ 35,760.04	$ 44,137.40	$ 99,970.03	####
15			$ (8,509.50)	$ -	$16,802.42	336048.48	$0.109	$ 36,648.68	$ 44,941.61	$ 144,911.63	####
16			$ (8,509.50)	$ -	$16,718.41	334368.24	$0.112	$ 37,559.40	$ 45,768.31	$ 190,679.94	####
17			$ (8,509.50)	$ -	$16,634.82	332696.40	$0.116	$ 38,492.75	$ 46,618.07	$ 237,298.02	####
18			$ (8,509.50)	$ -	$16,551.65	331032.92	$0.119	$ 39,449.30	$ 47,491.44	$ 284,789.46	####
19			$ (8,509.50)	$ -	$16,468.89	329377.75	$0.123	$ 40,429.61	$ 48,389.00	$ 333,178.46	####
20			$ (8,509.50)	-$21,000.00	$16,386.54	327730.86	$0.126	$ 41,434.29	$ 28,311.33	$ 361,489.79	####
21			$ (8,509.50)	$ -	$16,304.61	326092.21	$0.130	$ 42,463.93	$ 50,259.04	$ 411,748.83	####
22			$ (8,509.50)	$ -	$16,223.09	324461.75	$0.134	$ 43,519.16	$ 51,232.75	$ 462,981.57	####
23			$ (8,509.50)	$ -	$16,141.97	322839.44	$0.138	$ 44,600.61	$ 52,233.08	$ 515,214.65	####
24			$ (8,509.50)	$ -	$16,061.26	321225.24	$0.142	$ 45,708.93	$ 53,260.70	$ 568,475.35	####
25			$ (8,509.50)	$ -	$15,980.96	319619.12	$0.147	$ 46,844.80	$ 54,316.26	$ 622,791.61	####
Total			$ (212,737.50)	$ (42,000.00)	$424,570.15	8491403.08		$ 885,296.45	$ 622,791.61	$ 622,791.61	####

Figure 12: Updated Economic Model

The updated models were used to produce a set of recommendations for system size, financial agreement type, configuration and number of panels, and required auxiliary electrical equipment.

Appendix C1: Federal Engineering Standards and Constraints

Solar codes and standards are constantly changing and updating, so it is important to stay up to date. The main codes surrounding solar and its installation are National Electric code (NEC), international building codes (IBC), international fire codes (IFC), and structural engineering codes (ASCE). NEC 690 covers electrical safety requirements for PV systems. This includes the grounding equipment that is required, structure as equipment grounding conductor, PV mounting systems and devices, and adjacent modules. 690.4 (D) states that a PV system is permitted multiple inverters in or on a single building or structure, such that they are remotely located from each other and installed with a directory disconnecting means. Requirements are given for specific electrical situations. For example, ungrounded systems should comply with NEC 690.35, which requires disconnects, overcurrent protection, ground fault protection, conductors, battery systems, and marking on each junction box, combiner box, and disconnect. Grounded two-wire systems should have one conductor grounded or be impedance grounded, and the system should comply with NEC 690.5.

Underwriter Laboratories (UL) is a third party certification company that produces safety standards for products. A UL listed approval ensures the safety and serviceability of a product. It ensures that the product has been tested using nationally recognized safety and sustainability standards. NEC requires the racking equipment's UL listing to meet the required specifications of UL 703. The proposals we received typically listed the racking brand and UL listing, which we ensured met the requirements. The IBC covers flashing and attachments in article 1503.2. This code explains that "flashing shall be installed in such a manner so as to prevent water from entering the wall and roof" through any penetrations in the roof plane. Article 1509.7.2 requires radiant barriers covered with an approved roof covering so long as they both comply with the requirements of either FM 4450 or UL 1256. and structural loading considerations in section 3403. In articles 605.11.3.2.1 and 605.11.3.2.4 the IFC describes how modules (the panels) should be placed in order to provide a path for firefighters should they need to access the roof and additional clearance requirements concerning the placement of the panels. These codes require a 3ft clearance from the ridge of a pitched roof, both across the ridge of the roof and down along the side of the roof. The coverage ratio included in the model was determined as an industry standard that includes these placement codes.

The panels and racking themselves are produced with their own set of specifications. These specifics will not be known until a proposal is selected, and the specific system is known. One of the proposals we have received uses TerraGen TGR racking which includes detailed requirements for torque, tilt, equipment, bonding & grounding. During pre-assembly, all hardware must be torqued to 8 ft-lbs. When mounting the modules, the end clamp bolts must be torqued between 12-14 ft-lbs. For a ballast mounting, a block with a weight of 30-33 lbs is required. Their mounting system has been evaluated and conforms to a UL 2703 ranking. They have a UL 2703 Fire Class A rating. They also provide the racking's UL listing, as mentioned above.

Appendix C2: Virginia Engineering Standards and Constraints

There are specific state and city codes that companies should check before installing solar, should they further constrain the project. The Virginia Uniform Statewide Building Code (USBC), Virginia Statewide Fire Prevention Code (VSFPC), Virginia Energy Conservation Code, Virginia Construction Code, Virginia Existing Building Code, and Virginia Mechanical Code are all important standards for this project. USBC deals with solar systems and their requirements in section 3111. The Code of Virginia also includes multiple sections that discuss solar panels and their requirements. Code of Virginia § 15.2-2288.7. covers installing solar on residential, agricultural, commercial, industrial, institutional, and mixed use property. The code requires compliance with height and setback requirements in the corresponding zoning district. Specific zoning information can be found within local ordinances, which are detailed in the following section. Compliance with historic, architectural preservation, or corridor protection. Historic or architectural preservation may be adopted to buildings or structures having an important historic, architectural, archeological, or cultural interest. Such structures are prohibited to razed, demolished, or moved unless approved by the review board. Laws pertaining to small renewable energy projects are located in article five of the code.§ 10.1-1197.5- § 10.1-1197.11 defines the projects, talks about permits, the review process, limits, enforcement, right of entry, and information that needs to be given to the department of environmental quality. These articles define an energy storage facility as any energy storage equipment that can absorb, store, and redeliver energy. They define a small renewable energy project as a facility generating energy only from the sun or wind that does not exceed 150 megawatts.

Appendix C3: Charlottesville Engineering Standards and Constraints

The City of Charlottesville Code of Ordinances is another local standard to adhere to. A City of Charlottesville building permit will be required which is mentioned in Sec 5-56. Applications and fees for the permit may be submitted to the city's building official. The city of Charlottesville has a solar ordinance including standards for solar energy systems in Sec 34-1108. This code ensures the compliance of provisions stated in the USBC and VSFPC. They allow a solar energy system to be installed on the roof of a dwelling so long as it extends only up to 5 ft above the highest point of the structure. They also reference solar tax exemptions in Division 1 Sec 30-(126-138). Certified solar equipment and devices can be declared a separate class of property and are then allowed a classification for city taxation, so long as certain requirements are met. The exemption can be granted if: the title to the property is held by the person claiming the exemption, and the system is certified and inspected and shown to perform the purpose of providing for the collection and use of solar energy for an application which would otherwise require a conventional source of energy.

Appendix D: Technical Deliverables

Economic/Electrical Model

Electricity Model Equations:

1. Sets and Indices

- I: Set of years in the project lifetime
- J: Set of solar equipment types (panels, etc.)
- L: Set of available roof surfaces at the location

2. Parameters

Location-specific Parameters:

- H_{peak}: Average daily hours of peak sunlight ($kWh/m^2/day$)

Building-specific Parameters:

- S_l: Total square footage of roof l (m^2)
- p: Coverage ratio, the fraction of the roof that can be used for solar panels (dimensionless or %)

Solar Equipment Specification Parameters:

- E_j: Energy production capacity of equipment type j per year pre-degradation (kWh/year)
- $E_{j,i}$: Adjusted energy production incorporating panel degradation (kWh/year)
- A_j: Space required per unit of equipment type j (m^2)
- δ_j: Annual degradation rate of equipment type j (expressed as a percentage decrease per year, %/year)
- Eff_j: Efficiency of solar panel type j (expressed as a decimal or %)**
- Cap_j: Capacity of a single panel of type j (kW)
- $UsableArea_l$:Total area of roof surface l available for solar installations (m^2)

3. Decision Variables

- $x_{j,l}$: Number of units to install of equipment type j on roof l

4. Calculated Metrics

- Maximize Total Energy Production (kWh): $E_{total,\,i} = \Sigma_{i\in I}\Sigma_{l\in L}\Sigma_{j\in J}(\widehat{E}_{ij}x_{ij})$

5. Constraints

- Roof space constraint for each roof l: $\Sigma_{j\in J}(A_j x_{jl}) \leq S_l \rho \ \ \forall l\in L$

6. Key Equations

- $UsableArea_l = S_l p$
- *Usage Offset* ($Offset_i$) = ($E_{total,\,i}$ / $E_{usage,\,i}$)

- *MaxPanels* (x_{jl}) = [*UsableArea* / A_j)
- *Energy Production* $(E_j) = Eff_j(A_j * 0.092903) * H_{peak} * 365$
  - A_j adjusted to square meters
  - E_j: annual energy production in kWh per panel, pre-degradation
- *Adjusted Energy Production* $(E_{j,i}) = E_j(1-\delta_j)^{i-1}$
  - Reflects the degradation in panel efficiency over time
- $SystemSize = x_{jl} * Cap_j$

Economic Model Equations:

1. Sets and Indices

- I: Set of years in the project lifetime
- J: Set of solar equipment types (panels, inverters, etc.)

2. Parameters

Initial Investment Parameters:

- $C_{inverter}$: Cost of each inverter
- $C_{initial}$: Total initial investment for purchasing and installing the solar system
- PPW: Price per watt of the proposed system size (\$/W)

Operating and Revenue Parameters:

- M_i: Annual maintenance cost per kW ((\$/kW/year)
- P_{SRECs}: Price per SREC
- $E_{solar,\ i}$: Total electricity produced by the solar system in year i, derived from the electricity production model (kWh/year)
- *SystemSize*: Total installed capacity of the solar array (kW)
- U_i: Annual utility bill in year i
- $E_{usage,\ i}$: Total annual energy usage in year i (kWh/year)

Financial Analysis Parameters:

- P_0 : Initial cost to buy from the grid (\$/kWh)
- $R_{utility}$: Utility escalation rate (%/year)
- P_i: Utility electricity rate in year i, adjusted for the utility escalation rate
- D: Discount rate for NPV calculation (%)
- P_{PPA}: Price per kWh under the PPA (\$/kWh) (.095 per kWh, industry assumption)
- R_{PPA}: PPA price escalation rate (%/year)(1% per year, industry assumption)

3. Decision Variables

- x_j: Number of units to install of equipment type j
- *z*: A binary decision variable indicating whether SRECs are sold (1) or kept (0).
  - If z = 1, SRECs are sold, contributing to the NPV; if z = 0, there's no SREC revenue

4. Calculated Metrics

- Maximize NPV

$$NPV_{own} = -C_{initial} + \sum_{i=1}^{n} \frac{S_{electricity,\,i} + z \cdot R_{SRECS,\,i} - C_{maintenance,\,i} - C_{replacement,\,i}}{(1+D)^{i}}$$

  - $C_{replacement,\,i}$ is only included in the years when replacements occur.
  - $NPV_{PPA} = \sum_{i=1}^{n} \left(\frac{S_{PPA,\,i}}{(1+D)^{i}}\right)$

5. Constraints

- Non-negativity and Binary Constraints
  - $x_j \geq 0 \quad \forall j \in J$, $y_i \in \{0, 1\} \quad \forall i \in I$, $z \in \{0, 1\}$

6. Key Equations

- Yearly maintenance cost ($C_{maintenance,\,i}$) = SystemSize · M_i
- Annual electricity savings ($S_{electricity}$) = $E_{total,\,i} * P_i$
- Revenue from SRECs ($R_{SRECs,\,i}$) = ($E_{total,\,i}$ / 1000) * $P_{SRECs} * z$
- Initial system cost ($C_{initial}$) = $SystemSize * PPW$
- Number of inverters (V) = $SystemSize$ / 80
  - Rounded to nearest whole number
- Total inverter replacement cost ($C_{replacement}$) = $C_{inverter} * V$
  - applicable every 10 years or as per the inverter replacement schedule
- Adjusted rate of electricity per kWh (P_i) = $P_0(1+R_{utility})^i$

Appendix E: Citations

Gerhardt, N. (2023, September 14). *The Ultimate Solar Panel Maintenance Guide to Keep Your Panels Working as Efficiently as Possible.* Forbes Home. Solar Panel Maintenance Guide – Forbes Home

Mack, Eric. (2023, December 6). *Solar Lease vs. Power Purchase Agreement: Which Is a Better Deal?* CNET. Solar Lease vs. Power Purchase Agreement: Which Is a Better Deal? - CNET

Nicholson. (2022, October 17). *Fixing Solar Panels to Membrane Roofs.* Nicholson Roof Products. https://www.nicholsonsts.com/articles/fixing-solar-panels-to-membrane-roofs/.

Pivot Energy. (2022, March 2). *Solar Renewable Energy Certificates 101.* Solar Renewable Energy Certificates 101 (pivotenergy.net)

Wolf, Sara. (2024, February). *The Ultimate Guide to the USDA REAP Grant for Solar.* Paradise Energy Solutions. The Ultimate Guide to the USDA REAP Grant for Solar | Paradise Energy (paradisesolarenergy.com)