A Systems Methodology for Informed Solar Energy Decision-Making

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***Abstract*— Solar technology for buildings has flourished in recent years. The technology is becoming more popular in both the residential and commercial sectors. The process of purchasing solar is often complicated by different proposals from companies that cannot be directly compared. Changing government incentives, multiple financial models, the 25 year panel lifecycle, quickly changing technologies, structural limitations and diverse stakeholder motives make comparing proposals difficult. Presented through a case study of a non-profit in Charlottesville, Virginia, we propose a systems methodology for navigating this complicated landscape. This methodology involves working with stakeholders in the project to establish main objectives, identify current limitations, determine key decisions, and interpret metrics to measure success of a commercial solar project. These objectives, limitations, and decisions are used with financial and electricity models that we created to evaluate different metrics. Results from the models allow for direct comparison of different company proposals and system sizes.**

I. INTRODUCTION

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 systems approach is important, 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. A systems approach is key to understanding which decisions impact which objectives holistically, rather than one at a time. The importance of understanding the underlying systems becomes apparent when comparing different solar company quotes. Each quote, through making different assumptions about how their proposed design interacts with the larger system, takes more of a 'one at a time" approach. In a worst-case scenario, the quotes consider the solar project in isolation from the larger system. For example, in the case study presented in this paper, several solar companies' proposals maximized 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.

In this paper, we review the literature regarding methodologies for commercial building rooftop solar projects and then introduce a systems-based methodology and supporting models specifically for commercial building solar projects. We demonstrate the use of the methodology with a case study and discuss the implications of the case study for the approach.

II. LITERATURE REVIEW

While attempts have been made to help navigate the complicated solar process, most of the guides currently in existence allude to small-scale, residential solar installations. The U.S. Department of Energy (DOE), for example, has created user-friendly tools for homeowners and renters to estimate their home energy costs and "map out the best ways you can save money and energy" using government energy credits such as the Federal Tax Credit for Solar Photovoltaics [1]. The DOE provides easily comprehensible guides for solar-curious households including the "Homeowner's Guide to Going Solar," the "Homeowner's Guide to the Federal Tax Credit for Solar Photovoltaics," and a "Guide to Financing Your Rooftop Solar Energy System." While educating consumers on the process of solar and the legislative incentives available to them is one of the DOE's main priorities, their abundant resources are primarily focused on residential solar, leaving commercial customers with limited support.

Few models exist that both take a systems approach to conducting a solar project and are user- friendly to individuals unfamiliar with common solar terminology. For example, many models created are “destined to be of use to environmental government and local environmental authorities” [2]. Although these models are extremely productive and beneficial to the professionals interested in a consolidated technical model, it reduces the overall accessibility and use of the model. Another complication with the existing methodologies for conducting solar projects is the lack of standardized models that others can use and apply to their own projects. Existing research and case studies use methods specific to a building’s energy retrofit that cannot be replicated. Niccolo Aste and Caludio Del Pero’s “Energy Retrofit of Commercial Buildings: Case Study and Applied Methodology” for example, uses an “iterative process for energy audit and multicriteria analysis” to carry out energy retrofit of their unique insurance company commercial building in Milan, Italy [3]. However successful their methodology was for determining the feasibility of their case study’s commercial building energy retrofits, it is difficult for other commercial businesses to replicate the same process if inexperienced and curious in conducting a solar project.

Although there are “solar calculators" that aim to estimate installation costs and savings based on the inputted roof location and system size, few tools exist that encompass multiple key decisions, quantitative metrics, and main objectives. An example of one of these calculators is NREL’s PVWatts calculator, which claims to estimate the energy production of grid-connect photovoltaic (PV) energy systems throughout the world [4]. Its goal is to “allow homeowners, small building owners, installers, and manufacturers to easily develop estimates of the performance of potential PV installations.” After determining the user’s latitude and longitude based on an inputted address, it enables the user to insert system size, module type, array type, system losses (%), tilt, and other advanced parameters to achieve a solar system output for the desired location. As useful as calculators such as PVWatts can be, they are tools that can plug into an overall systems approach more so than being a holistic approach. They 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.

III. METHODOLOGY

Implementing a systems approach for commercial rooftop solar installations involves considering the interconnected factors that affect the project. The approach involves identifying objectives and constraints to measure the project's environmental and economic success, specifying key decisions, and using models to connect the decisions to performance measures.

A. Measuring Project Success

Identifying the main objectives of a solar project is vital in measuring its success. The company could have environmental objectives such as aiming to lessen their carbon footprint through using solar energy. The company might also have economic objectives such as saving money. Quantitative metrics for environmental objectives could include the amount of electricity produced by solar and the percent of electricity offsetted by this solar production. Quantitative metrics for economic objectives could 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. These could include social objectives like striving to set an example for a community or providing educational opportunities, and also additional objectives such as maintaining or improving the aesthetics of a building. While some metrics are difficult to quantify, they can still be measurable.

In addition to objectives, identifying constraints within which any solution must operate is critical. Commercial rooftop solar projects are constrained by a few common factors such as the structural capacity of the building, size of the roof, the financial investment required, and limitations from federal or local codes.

B. Design Decisions

Key design decisions for commercial rooftop projects include the number of panels, their placement, and the mounting system used to attach the panels. These decisions impact other decisions (e.g., the number of inverters needed) and drive the overall system's performance. 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. 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 [5].

The type of mounting system can affect the number of panels that can be placed on a roof. The ballasted mounting system is effective for roofs that should not be penetrated; however, it involves a significant amount of additional weight. Choosing this mounting system may result in installing fewer panels, depending on the weight capacity of the building. Bonded installations are lighter, allowing for more panels on a roof that has a smaller allowance for additional weight. This system is more expensive, so the price limits the number of panels that can be added. The key design decisions reviewed in this section are constrained by structural capacity, roof size, budget, and codes. Building codes specify certain load requirements for roofs, and adding solar panels can put this specification in danger. A structural engineer can determine if adding solar panels to a roof is viable within the load requirements for the building. The solar companies can then design the layout of the panels on the roof.

C. *Financial Decisions*

Economically, two important decisions must be considered: choosing the appropriate financial agreement and identifying local, state, and federal programs that incentivize solar, such as selling Solar Renewable Energy Credits (SREC). Two main types of financial agreements are an owned system and a Power Purchase Agreement (PPA). In an owned system the business owner purchases the panels upfront and is responsible for all maintenance and installation costs. In a PPA, a third party owns and maintains the solar system installed on the customer's building. PPAs charge a fixed rate per kilowatt of energy produced by the system [6].

Solar Renewable Energy Certificates (SRECs) are created for each megawatt-hour of electricity generated from solar energy systems [7]. A key economic decision is deciding whether to sell the SRECs or keep them to reduce a business's carbon footprint. The amount earned from selling SRECs varies by state. Local, state, and federal governments often incentivize solar through grants and credits. The Inflation Reduction Act (IRA), provides up to a 30 percent credit for qualifying investments in solar energy projects [8]. The Rural Energy for America Program (REAP) Grant provides financial assistance to rural for-profit small businesses purchasing renewable energy systems [9].

D. *Electricity Production Model*

The electricity production model is a tool to evaluate the energy output from 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. Location specific parameters include peak sunlight hours. 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.

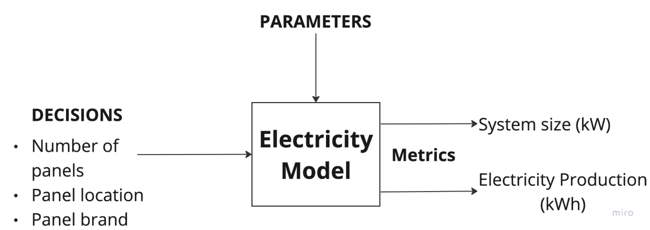

Figure 1. Electricity Production Model

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_i: 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)
- $UsableArea_i$: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

- $UsableArea_i = S_l p$
- *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* $(E_{j,i}) = E_j(1\text{-}\delta_j)^{i-1}$
  - Reflects the degradation in panel efficiency over time
- $SystemSize = x_{jl} * Cap_j$

E. Economic Model

The economic model 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. 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.

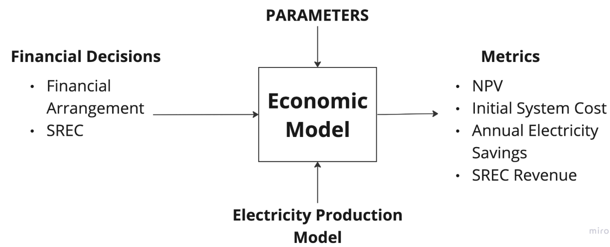

Figure 2. Economic Model

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

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

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

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) = $P_0(1+R_{utility})^i$

IV. CASE STUDY

The systems approach detailed in the prior section is applied to a local nonprofit in Charlottesville, VA. While saving money on electricity is one objective, their main objective is to use the solar project as part of their educational mission and to be a community leader in the clean energy transition.

The facility pays monthly electrical bills that range from \$10,000-\$20,000 and consumed over two million kWh in 2022. 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. The building has four separate Thermoplastic Polyolefin (TPO) roof sections, (three are flat, one has a minor slope) that should not be punctured. These conditions constrain the project. The roof material requires the mounting type to be ballasted. The ballasted mounting is not suited for the section of the roof that is slanted and adds significant weight.

Four companies provided solar quotes with sizes ranging from 642 panels to 815. The proposals were either PPAs or owned systems with the owned systems ranging in initial investment from \$787,000 to \$1.1 million before incentives. The solar system sizes ranged from 350 kWh - 480 kWh (21-28% offset). To validate the models we used the assumptions from the proposals to recreate each quote. The team then utilized the validated electrical and economic models to evaluate the proposals under a common set of assumptions along with the location and building specific parameters.

A. Electrical Production Model

Location and building specific parameters:

- H_{peak} : 4.5 hours/day in Charlottesville
- S_l: 44,712 sqft for the building

TABLE I. Electricity Model Outcomes Compared to Quotes

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

Table I 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.

B. Economic Model

Project specific parameters

- U_i: \$145,345 for year 1
- $E_{usage,\ i}$: 2,137,547 kWh/year for year 1

- P_i: \$0.07 for year 1

The model considers two configurations on the roof:

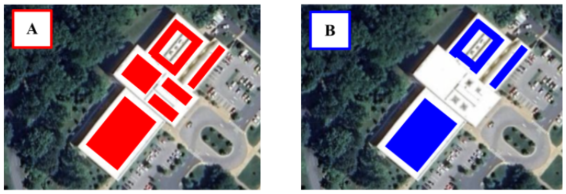

Figure 3. The two configurations of solar panels that the model considers

TABLE II. Economic Model Outcomes Compared to Quotes

	Electricity Model Outcomes Compared to Quotes					
			Proposal		***Model***	
	Finance Plan	***Prop-osal***	***NPV ($)***	***Payback Period***	***NPV ($)***	***Payback Period***
A	Owned	Co. 1	197k	17 years	202k	16 years
	PPA	Co. 2	-145k	N/A	-150k	N/A
	PPA	Co. 3	N/A	N/A	-200k	N/A
B	Owned	Co. 4	194k	18 years	198k	16 years

It is important to note the proposal NPVs were calculated by the authors as all 4 quotes only provided 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 likely make A not feasible making configuration "B, owned" the optimal choice for fulfilling all objectives. The inputs and results show the complexities of real situations and the necessity of a systems approach. The case study ultimately shows how considering a holistic range of measures and objectives, comparing alternative designs, and using shared assumptions can help companies make more-informed decisions.

V. LIMITATIONS

The model relies upon the estimation of several parameters such as price per kW of power and coverage ratio, only to name two. The economic model does not investigate leasing and does not account for economies of scale. Additionally, the format of the model is Microsoft Excel which will likely not be intuitive for many users, an online platform with an easy-to-use interface could be a future improvement on the above model and methodology.

VI. CONCLUSION

The objective was to create a model that helps familiarize a commercial-sized building owner with the solar process. This involved receiving quotes from solar companies and contacting a structural engineer to understand limitations. The model estimates the NPV and the building's best panel configuration. This methodology was used in a case study of a non-profit in Charlottesville, VA. The model can be adopted for use anywhere in the U.S. by changing the parameters to match the location and building of interest.

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