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Research Report: ZLC-2010-11
Sourcing Strategies for a Photovoltaic Power Plant
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Sourcing Strategies for a Photovoltaic Power Plant

By Mani Ponnuswamy

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Summary:
This thesis studies the dependence of a photovoltaic (PV) power plant's lifetime cost and lifetime revenue on the choice of its solar PV panels. An actual power plant located in Germany is modeled in Matlab using the electrical parameters of its PV panels. The plant's panels in the model are then sequentially replaced with 98 different types of panels and individual simulations are run for each type. Based on the results, a generalized framework for choosing solar panels and its suppliers is developed.

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KEY INSIGHTS

1. The selection of the optimum PV panel for a chosen site is independent of its nameplate power rating and its country of manufacture.

2. A simulation-based approach for PV panel selection is necessary to achieve optimal tradeoff between lifetime revenue and lifetime cost.

3. A payback period-based approach is not capable of distinguishing significantly between PV panels.

Introduction

Procurement questions such as 'What is the right technology for my product?' and 'What criterion should I use to buy material?' are very crucial for solar photovoltaic (PV) power plant projects where material costs are a substantial portion of total lifetime cost. This research builds a framework to help answer some of these questions in the solar PV supply chain context.
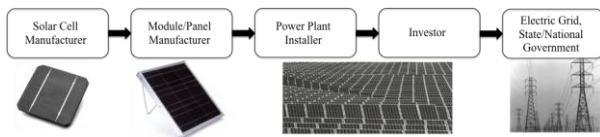

In this research, the PV chain (shown above) is viewed from the perspective of a solar power plant installer - the solar PV supply chain participant who is responsible for deploying PV systems outdoors. The analysis has been done with the intention of maximizing the supply chain profitability of the segment of the chain between the solar panel manufacturers and the end customers. The analyses and conclusions in this research rely upon cost and energy yield data obtained from a 1.512MWp ground-mounted, solar PV power plant constructed in Germany by The Company in 2008. The PV plant is modeled in Matlab using the electrical parameters of its PV panels. The plant's panels are then sequentially replaced with 98 other panel types and the lifetime cost and lifetime revenue are computed for each type. Finally, the findings and conclusions based on the results are generalized so that they are applicable to any PV power plant project.

The Company and its PV Plant

The Company performs engineering, procurement and installation activities for rooftop and ground-mounted solar photovoltaic systems. In the case of the solar PV plant built by The Company in 2008, the customer already had a "feed-in tariff pre-approved" site. The Company had a fixed budget but was free to choose the installed capacity and the solar PV panel type as well as its suppliers. A 1.512MWp system composed of 8460 mono-crystalline panels was decided upon. The Company chose Chinese modules because (1) German panels were more expensive, (2) Chinese panels had no known quality or reliability issues and (3) there were no incentives that made German panels more attractive. In addition, German panels were usually difficult to procure for domestic use since about 60% of them were sold in the export market. The PV panels were ordered from the supplier 2 months ahead of project commencement. Once the components arrived at the site, it took 15 men and 4 weeks to prepare the land, build the mechanical support structures, unload, sort and install the

panels, and wire them to all the other electrical components. The result was a 1.512MWp plant with 3 separate power generation stations that were equipped with systems of 2880 170Wp panels, 2880 175Wp panels and 2880 180Wp panels respectively. In addition to the power generation system, the plant was also equipped with a weather station (to record solar irradiance and ambient temperature levels at the panel surface every minute) and a power monitoring system that collects data on the operating conditions and the output power of each of the systems. The figure below shows the breakdown of the total installed cost of this plant. Note that solar panels contribute the most to the cost.
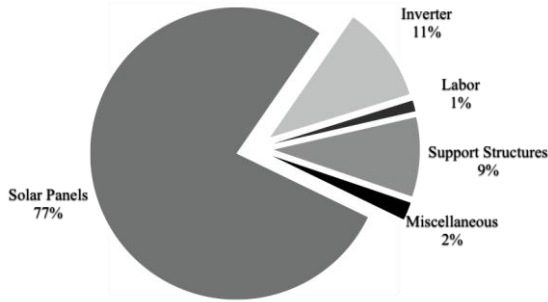
The Model

Matlab was used to build the model used in this research. A functional representation of the model is shown in the figure below.
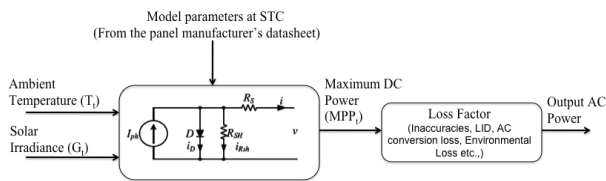
Once the model is configured with the panel's electrical parameters (obtained from the panel manufacturer's datasheet), it can provide the maximum power achievable (MPP_t) from that panel for any given combination of solar irradiance (G) and ambient temperature (T_{amb}). The equations underlying this model are non-linear and complex due to the electrical characteristics of the photoelectric material and the Newton-Raphson numerical method is used to solve them. The model is validated using 4 different panel types (2 mono-crystalline, 1 poly-crystalline and 1 thin-film) and it is found that the model's characteristics are in very good agreement with the characteristics reported in the datasheet. The algorithm, underlying equations and the validation results are omitted here due to space constraints but are available in the thesis document. To account for losses such as direct current (DC) to alternating current (AC) conversion loss, mismatch, and environmental losses such as shading and soiling, a multiplicative loss factor is incorporated into the model.

Also, to achieve a good trade-off between minimizing estimation error and minimizing computational effort, data averaged over 15-minute intervals was chosen for this work. Energy over the 15-min interval (E_{15min}) and the annual energy yield

(E_{annual}) are computed from the 15-min power (P_{mpp}) using the following formulae.

$$E_{15min}(i) = \frac{P_{mpp}(i)}{4} \qquad E_{annual} = \sum_{i=1}^{35040} E_{15min}(i)$$

where 35040 corresponds to the approximate number of 15-min intervals in a year.

The model is configured with the panel's parameters and simulated with G, T_{amb} conditions at the plant's physical location in the year 2009. A comparison between simulation and actual measurement for two days in May 2009 is shown below (Energy is in units of kWh and time is in hours).
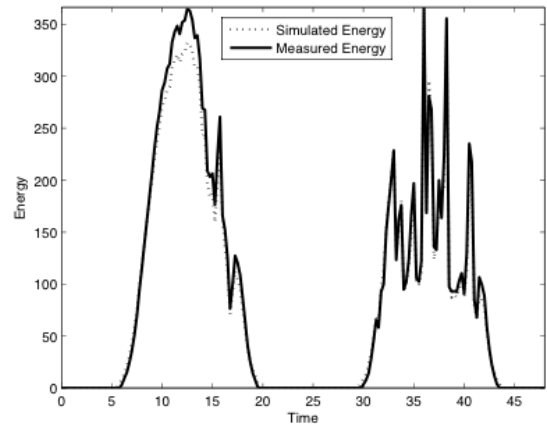
The annual energy yield from 2009 obtained from simulation is within 1% of actual measured yield. This further proves the model's validity.

A Counter-Intuitive Behavior in PV Panel Yields

Between two panels from the same supplier, belonging to the same technology with identical manufacturing processes, one would expect the panel with a higher nameplate power rating to be more "powerful". However, actual data from the plant as well as simulation data show otherwise. This can be seen in the following figure where, for certain G and T_{amb} conditions, a 175Wp panel performs better than an 180Wp panel. In fact, for the conditions at the plant in 2009, the 175Wp panels generated 3.5% more energy than the 180Wp panels!
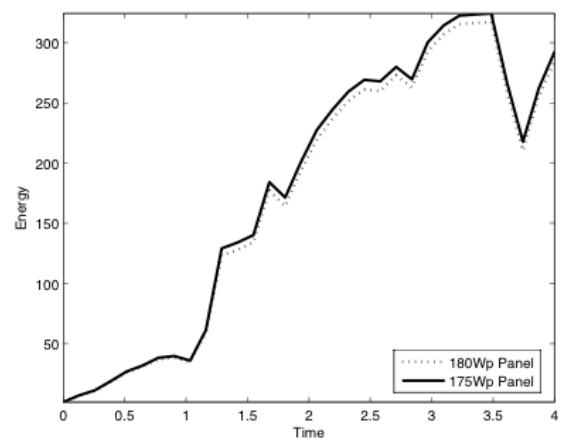
This counter-intuitive behavior may be explained as follows. Nameplate power ratings on PV panels are based on laboratory measurements at standard test

conditions (G=1000W/m^2 and T=25C). However, these conditions are almost never realized in real-life. Besides, due to the inherent non-linear dependence of power on G and T$_{amb}$, it is impossible to correctly estimate a PV panel's performance without the use of simulation models. Given that panel prices are directly proportional to their nameplate power ratings, this finding has cost implications as well. This behavior further exemplifies the need for a mathematical simulation model such as the one developed in this thesis to project energy yields of panels before making sourcing decisions.

Lifetime Energy Yield and Lifetime Cost

Once the first year's energy yield (E$_1$) and cost of panels (C$_{panels}$) are known, the lifetime energy (E$_L$) and lifetime cost (C$_L$) are computed as follows.

$$E_L = E_1 \left(\frac{1 - (1 - dr)^L}{dr} \right)$$

$$C_L = C_{panels} + 12000 + 8000\,(L - 1)$$

where L=20 is the plant's lifetime in years, dr is the panel's performance degradation rate (1% for crystalline and 3% for thin-film), €12,000 and €8,000 correspond to the O&M cost in year 1 and years 2...L respectively.

Next, the model is sequentially configured with electrical parameters from the datasheets of 98 other panels and E$_L$ and C$_L$ are computed for each panel.

Results

The results of lifetime energy versus lifetime cost of 61 panels are shown in the following figure. The panels have been differentiated according to the country of manufacture.
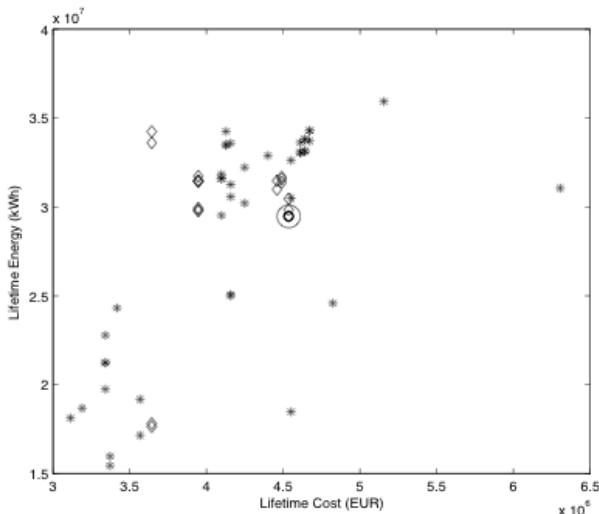

◇ - *Foreign Supplier;* ∗ - *Domestic Supplier;* ◯ - *Currently installed panel*

It is interesting to note the presence of a crystalline module from a foreign supplier that provides better performance both in lifetime energy yield and lifetime cost. Simulations show that choosing this

panel instead of the currently installed panel would result in a 15% increase in lifetime energy while simultaneously cutting down lifetime costs by 19.5%!

A comparison of the cumulative revenues for three panel options is shown in the figure below. The calculations have been done with a €0.4675/kWh feed-in tariff corresponding to the German EEG policy for solar plants installed in 2008. It is interesting to note that, while the largest revenue option yields almost twice the lifetime revenue of the lowest cost option, the payback period is almost the same for the three panels. In fact, 75% of the panels simulated had payback periods of 6 to 7 years, regardless of the technology or the supplier location.
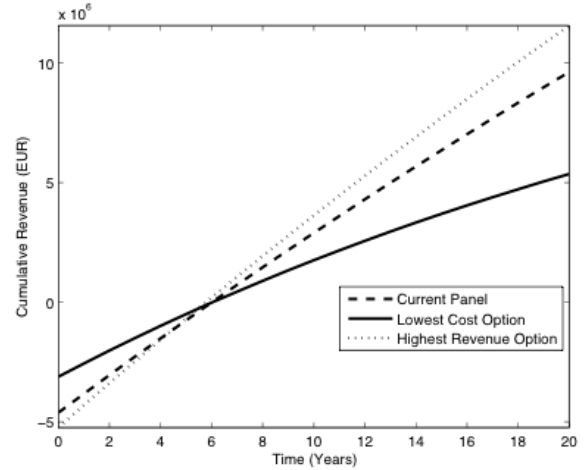
The following table summarizes the sample statistics of the results from the 99 panels simulated.

Statistic	Lifetime Revenue	Lifetime Cost	Payback Period
Range (in %)	133%	105%	80%
Coefficient of variation	0.20	0.13	0.14
Deviation of current panel from ideal	15%	32.5%	27%

There were some marked differences between some panels. For example, a panel with a lifetime cost of €3.6 million resulted in a 122% increase in lifetime revenue over another that cost only 8% lesser! It was also seen that the two best panels for this power plant (in terms of lifetime revenue minus lifetime cost) perform within 4% of each other. One is a 175Wp panel from a domestic supplier and the other is an 185Wp panel from an international supplier. It is reasonable to infer that neither the maximum power rating nor the country of manufacture seem to influence the profitability.

Conclusions

There are immense opportunities to increase the solar PV supply chain surplus in the form of optimal sourcing of PV panels. Incentives in the PV supply chain should be aligned so that every participant is working towards increasing this surplus. This thesis shows the importance of simulation models for choosing optimal panels for a chosen site. Moreover, the lifetime energy-lifetime cost chart that has been suggested could be an effective tool for supplier negotiations as well as to assess the financial viability of the project.