PHOTOVOLTAIC ENERGY SYSTEMS: A FEASIBILITY STUDY

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Abstract

The Industrial Revolution has brought an enormous increase in the use of fossil fuels, specifically oil, coal and natural gas. The combustion of these fuels releases many gases that are harmful to humans and the rest of the ecosystem. Therefore, increasing energy efficiency including the use of renewable energy is heralded as the most effective strategy to reduce air pollution and hinder anthropogenic climate changes.

In this study, the viability of photovoltaic (PV) systems was investigated via a case study involving a shopping center. Engineering, environmental, and economic aspects were thoroughly examined and, as a result, a grid-connected PV system was designed to satisfy various system constraints. Engineering factors such as optimal array orientations, shading effects, module sizing, and compatibility issues were analyzed using the PV Watts method. The environmental analysis took into account not only the amount of pollution avoided over the lifetime of the system but also the energy extended during the manufacturing process. Additionally, various capital budgeting and sensitivity analyses were presented including the grid-parity technique for optimal conditions. Finally, advances in smart-grid technologies for integrating distributed energy sources were suggested for further studies.

Introduction

Renewable energy, including the use of Photovoltaic (PV) systems, has extensively been discussed in the literature. However, most of the studies [1-20] dealing with the design and applications of PV systems, were limited in scope and, therefore, did not cover all of the underlying issues involved in the process. In this study, the feasibility of PV systems was thoroughly investigated, taking into consideration not only engineering aspects, but also economic and environmental factors, thus providing a more comprehensive approach to the study of PV systems. Although PV systems do not emit any pollution during their operation, manufacturing its various components does require a substantial amount of energy. Thus, the environmental study presented here takes into account the amount of pollutants avoided over the lifetime of the system and also the time it takes to recover the energy that went into the manufacturing process.

For the economic analysis, capital budgeting techniques were utilized to determine the net present value and internal rate of return based on estimated cash flows over a 30-year period. Furthermore, the market analysis provided techniques to predict the cost and performance of PV systems such as inverter lifespan, future inverter costs, and module degradation. These estimates, along with the expected trends in electricity costs, were incorporated into the cash-flow analysis in order to provide a more realistic solution. In this paper, several design-optimization strategies to reach grid parity at certain government incentive levels are proposed.

Case Study

The viability of photovoltaic (PV) systems to produce clean electricity was investigated via a case study involving a shopping center located in the southeastern region of the United States. This case study was conducted to address key factors involved in the planning and designing of large PV systems such as optimal array orientations, shading effects, and compatibility issues between the PV arrays and inverters under various weather conditions. Different capital budgeting techniques were also investigated to determine if installing PV systems in this part of the country is feasible under the prevailing environment and economic conditions. For the purposes of this study, solar data was obtained from the National Renewable Energy Laboratory (NREL) software [2], PVWatts (V2), based on analysis of the National Solar Radiation Data Base (NSRDB). While calculations are based on historical data, the actual performance of the PV system will be valid within 10 to 12% of the calculated values [3].

Engineering Aspects

Solar irradiation is the total amount of solar energy collected on an area over time and is typically expressed in kWh/m^2. At most locations on Earth, solar irradiation will peak around 1kW/m^2 every day around solar noon. Insolation is the term used to gauge the solar energy that reaches the Earth's surface over the course of a day. It is usually expressed in kWh/m^2/day. PV modules should ideally be facing the sun to collect maximum power. This can be achieved by using a sun-tracking system that automatically orients the array to the position of the sun. However, sun-tracking is usually used for smaller applications and rarely roof mounted, as it may cause structural problems [7].

The proposed site for the PV installation was a shopping center served by a 3-phase, 480-volt feeder. The shopping center operates 24 hours a day, 7 days a week. Its electricity use over a five-year period is shown in Figure 1.

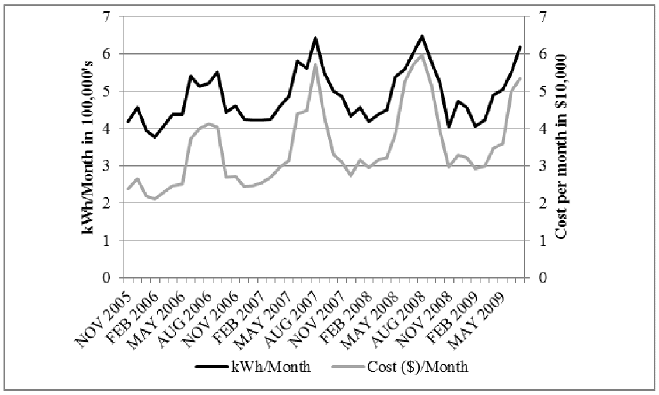

Figure 1. The Energy Profile for the Shopping Center

The cost of energy incurred by the facility fluctuates throughout the year, costing more in summer than other months during the year. The cost per kWh is depicted in Figure 2.

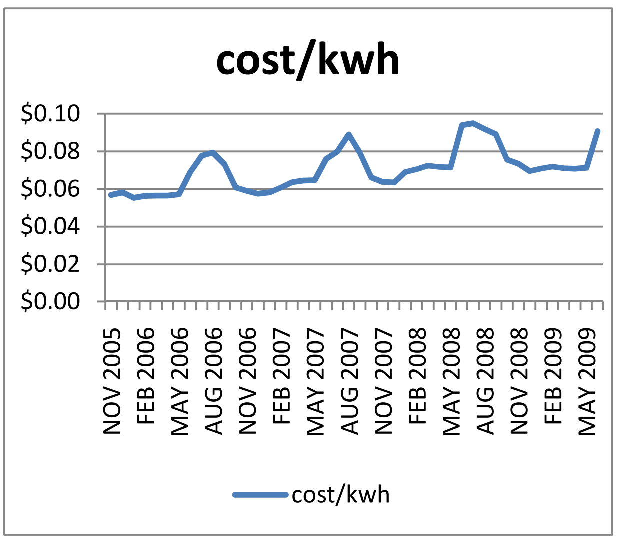

Figure 2. The Energy Cost for the Shopping Center

The solar insolation received for fixed arrays facing due south at various tilt angles is shown in Table 1. Since the best of these array angles changes throughout the year, it may be more economically feasible to mount the modules on an adjustable platform and adjust the tilt angle as needed. This arrangement should allow the array to be tilted at 32.3° during March, at 17.3° from April to September, and at 47.3° between October and February, resulting in about 7.2% energy increase over a fixed-array arrangement.

Table 1. Available Solar Insolation in kWh/m^2/day

	17.3°	32.3°	47.3°	Best of
JAN	3.68	4.17	4.42	4.42
FEB	4.51	4.91	5.03	5.03
MAR	5.46	5.67	5.56	5.67
APR	6.42	6.29	5.80	6.42
MAY	6.19	5.78	5.08	6.19
JUN	6.27	5.74	4.93	6.27
JUL	6.29	5.83	5.07	6.29
AUG	5.51	5.28	4.79	5.51
SEP	5.51	5.58	5.35	5.58
OCT	5.09	5.46	5.52	5.52
NOV	4.03	4.55	4.81	4.81
DEC	3.61	4.17	4.49	4.49
YEAR	5.22	5.29	5.07	5.52

Rack systems manufactured by IronRidge were considered in this study with mount models UNI-GR/12H and UNI-GR/14H capable of holding 7 and 8 PV arrays, respectively. Shading on PV modules can cause a significant drop in energy production. The Solar Pathfinder, a popular instrument to measure shading, was used in this study. It contains a convex transparent dome placed over a sun-path chart. When properly oriented, the reflection of the dome provides a comprehensive solar/shade evaluation for the entire year.

The cost of energy incurred by the facility fluctuates and several pictures were taken by the Pathfinder from different sites of the proposed locations. Each picture was then analyzed by the Solar Pathfinder Assistant program to determine the site efficiency for each location. The site efficiency is a measure of how well each site will collect solar energy after factoring in the dates and times of possible shading. This includes any losses that may occur if the proposed site happened to deviate from the optimal orientation defined at a tilt angle of 32.3° and an azimuth angle of 0° (due south).

For example, a site with optimal orientation will have 100% efficiency if no shading occurs throughout the entire year. Three locations on the roof of the building were selected for analysis with the results shown in Table 2. As depicted, all three areas were considered excellent PV sites for their near-optimal shading efficiency.

Table 2. Shading Evaluation by the Solar Pathfinder

	# of readings	Shading Factor
South Side	8	99.38
Center	11	99.3
North Side	11	98.67

Table 3. Array Spacing Calculation

array tilt angle	47.3°	32.3°	17.3°
module length (m)	1.65	1.65	1.65
array height (m)	1.21	0.88	0.49
mount length (m)	1.12	1.40	1.58
solar alt angle	20°	20°	20°
shadow length (m)	3.33	2.42	1.35
solar azimuth angle	45°	45°	45°
distance between rows to prevent shading (m)	2.61	1.90	1.06
total space need for row (m)	3.74	3.30	2.63

PV systems are designed so that the operating voltage of each module string always falls within the maximum power point tracking (MPPT) voltage range of the inverter. Most inverters are equipped with MPPT circuits to ensure that arrays produce maximum power under varying temperatures and solar irradiance. The maximum number of modules in a string can be found by the quotient of the MPPT input voltage of the inverter, Vmax (INV) and the open-circuit voltage of the module (V_{OC}) at the coldest operating temperature.

The minimum number of modules is found by rounding up the quotient of the inverter minimum input voltage at MPPT and model voltage at the maximum expected temperature. The DC input current of the inverter is the sum of the currents of all the strings or, more simply, the product of the number of strings and module current. The maximum number of strings is found by dividing the maximum input current of the inverter by the module short-circuit current at the maximum module operating temperature [4].

The ratio of the PV array power to the nominal AC power output of the inverter is called the inverter sizing ratio. The ideal sizing ratio is typically greater than 1 to account for any module mismatch, soiling, aging, and wiring losses. An inverter ratio around 1.15 is very common in the PV industry [5]. When a system has an inverter sizing ratio higher than 1.3, there will be significant energy losses and premature aging of the inverter. An inverter sizing ratio that is too small will make overloading the inverter less likely, but having too few modules could harm the economic performance of the system. However, it has been found that the economic performance of PV systems with inverter efficiencies around 98% is less sensitive to variations in inverter sizing ratio [6].

Due to space limitations, a PV system rated at a 286.44kW was originally designed to fit the site location. However, a smaller system rated at 152.5kW was found to reach the grid parity resulting in a more attractive return on investment. Both options were considered in this study to provided a comparison between the two systems. Arrays sizing are presented in Table 4.

Table 4. Arrays Sizing Calculation

Hottest Day (°C)	40.6	40.6
Coldest Day (°C)	-16.1	-16.1
temp rise coef (°C/kW/m^2)	20	20
max solar irradiance (kW/m^2)	1.3	1.3
module temp at hottest day	66.6	66.6
Inverter Model	SC250U	Satcon
Nominal AC output	250	135
max input voltage	600	600
maximum MPP voltage	600	600
minimum MPP voltage	330	310
max DC input current	800	454
inverter efficiency	97.0%	96.5
Voc at coldest temp	25.70	25.70
max power at hottest temp	15.25	15.25
Isc at hottest temp	12.36	12.36
string Voc at coldest temp	565.5	565.5
string max power at hottest temp	335.6	335.6
max # of series connected modules	23.3	23.3
min # of series connected modules	21.6	20.3
# of modules in series	22	22
max # of strings	64.72	36.7
# of series strings	62	33
total # of modules	1364	726
inverter sizing ratio	1.15	1.13

The method for estimating the performance of PV systems is discussed in this section. It is based on the PVWatts (V2) program developed by NREL [2]. Various losses associated with PV systems are shown in Table 5. According to NREL, PV modules should be derated by 1% each year after installation [8]. Energy and revenues generated by the 286.44kW system are shown in Table 6.

Table 5. Derate Factors used for Calculations

Component Derate Factors	PV Watts Default	NREL suggested Range	Derate Factor
PV module nameplate rating	0.95	0.80–1.05	.95
Inverter and transformer	0.92	0.88–0.98	.97
Mismatch	0.98	0.97–0.995	.98
Diodes and connections	0.995	0.99–0.997	.995
DC wiring	0.98	0.97–0.99	.98

AC wiring	0.99	0.98–0.993	.99
Soiling	0.95	0.30–0.995	.95
System availa-bility	0.98	0.00–0.995	.98
Shading	1	0.00–1.00	.9934
Sun-tracking	1	0.95–1.00	1
Age	1	0.70–1.00	1
Total	.77		.806

Table 6. PV Watts Analysis for the 286.44 kW System

Month	Insolation (kWh/m2/day)	kWh produced	Value $
Jan	4.17	28,581	$2,239
Feb	4.91	30,467	$2,387
Mar	5.67	38,190	$2,992
Apr	6.29	40,141	$3,145
May	5.78	36,890	$2,890
June	5.74	34,646	$2,715
July	5.83	36,472	$2,858
Aug	5.28	33,197	$2,601
Sep	5.58	34,296	$2,687
Oct	5.46	35,474	$2,779
Nov	4.55	29,682	$2,326
Dec	4.17	28,682	$2,247
Year	5.29	406,719	$31,866

Financial Analysis

A review of the literature revealed a range of assumptions that go into estimating the engineering and financial performance of PV systems. For instance, yearly electricity price inflations between 6.7% [9] and 7% [10] may be used for financial analysis. Module degradation rates may vary between 0.5% and 1.0% per year [8]. PV modules have life expectancies of up to 40 years [10] but inverters need to be replaced every 5 to 10 years [11]. The price of inverters is expected to decrease by 35% in 10 years and by 50% in 20 years [11]. The typical weighted average cost of capital for such a facility is around 7.04% [12] and an appropriate discount rate for PV systems is 4% to 6% [13]. A study conducted in 2008 by the Lawrence Berkeley National Laboratory [14] set the average cost of rack-mounted PV systems (>100kW) to $7.20 per installed watt capacity or $7.28 in today's dollars [15]. At this rate, the price of the 286.44kW, PV system is about $2,085,283 but would only cost $959,698 after the 30% federal tax credit and the 35% state tax credit [11] have been applied.

The financial analysis conducted was based on Brigham and Ehrhardt's capital budgeting methods [16]. The cash-flow estimates were based on a yearly electricity price inflation of 6.7%, module degradation of 1.0% per year, 30-year system life with the inverter replaced every 10 years, and a 7.0% capital cost. The net present value (NPV) is the amount of money saved or spent as a result of investing in the PV system. Sensitivity analysis is a powerful tool that provides alternative scenarios as assumptions are varied. For the base-case scenario presented in Figure 3, the NPV and the internal rate of return (IRR) were found to be -$218,214 and 5.19% respectively.

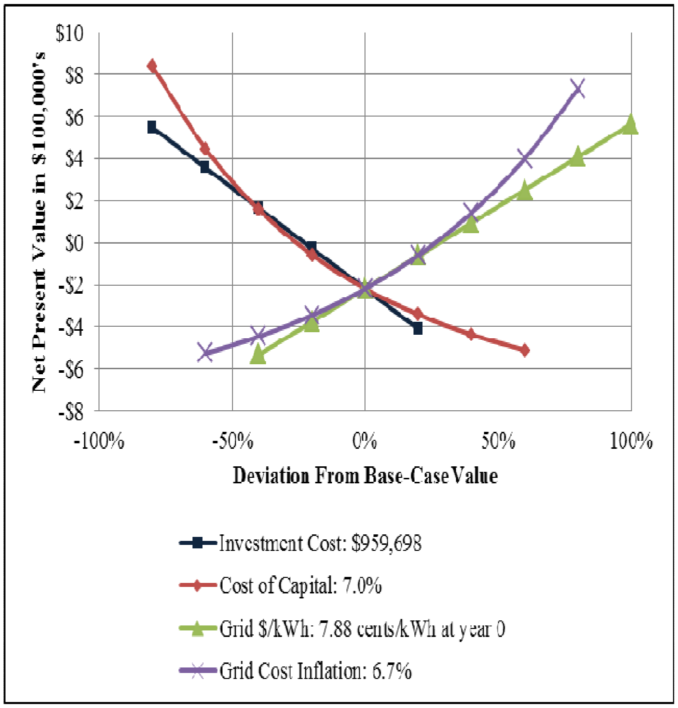

Figure 3. Sensitivity Analysis for the 286.4 kW System

The PV energy presented in Table 6 is very conservative in nature and may as well be the worst-case scenario for this case. Another important factor to consider is the cost of electricity. Currently, the state average kWh price of 8.44¢ is relatively low compared to the rest of the country. Many states have higher electricity prices such as California (13.1¢) and New York (15.4¢), which make PV systems more attractive investments to undertake [18].

Optimal Conditions

The sensitivity analysis (Figure 3) determined that the project return is not sufficient to cover the cost of capital investment even after all of the government incentives were utilized. The fact that the NPV is negative suggested that this particular PV system is not optimal since it has not reached grid parity, where the cost of photovoltaic electricity is equal to or less than the price of electricity [17]. However, this result should not imply that the system is not feasible since small deviations in the sensitivity analysis may lead to different conclusions. For instance, a 12% energy increase under favorable weather conditions could lead to a positive NPV, rendering the system profitable.

Under the current circumstance, it is feasible to design an optimal PV system if the government incentives cover at least 64.4% of the total cost. The government incentives for the 286.4kW system, including the state tax credit, amounted to only 54% of the system cost. Therefore, it was determined that a smaller system with a DC rating of 152.5kw would achieve the optimal results. The sensitivity analysis for this case is provided in Figure 4 in which the NPV and IRR were found to be + $3,682 (positive) and 7.07%, respectively.

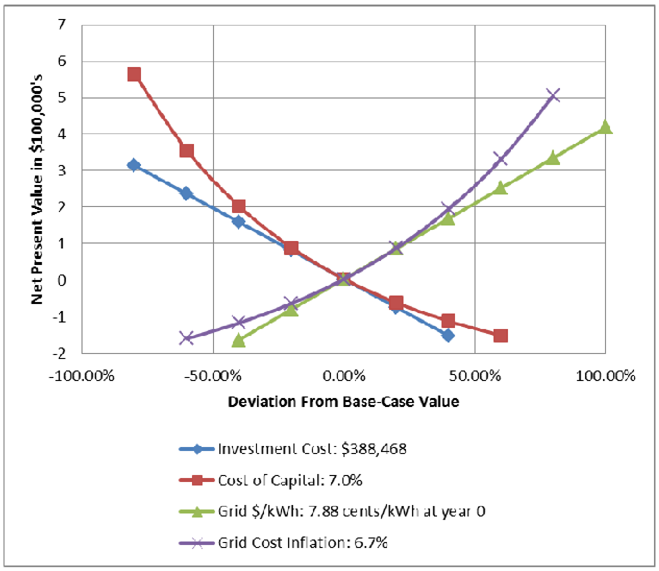

Figure 4: Sensitivity Analysis for the 152.5kW System

Environmental Analysis

Two aspects were considered for this environmental analysis: the energy payback and the amount of pollutants avoided over the lifetime of the PV systems. Photovoltaic systems do not emit any pollution or carbon dioxide during their operation. However, manufacturing the components of PV systems does require a substantial amount of energy. The amount of time that it takes for a PV system to recover the amount of energy that went into manufacturing the components is called the energy payback per years.

The Evergreen ES-A-210 module, made from multi-crystalline silicon, has a minimum efficiency of 13.4% and requires no more than 650kWh/m^2 of energy to manufacture [19]. Here, the received solar energy is about 1,932kWh/m^2/year. Therefore, the energy payback for the ES-A-210 module is calculated to be around 2.51 years. The module frames and the other components typically have an energy payback period of 1.8 years; thus, the proposed 152.5kW system is expected to have a total energy payback period of 4.31 years.

Conventional power generation plants use fossil fuels that release various pollutants and greenhouse gasses. The amount of chemicals emitted for every 1MWh of electric energy produced has been published by the Environmental Protection Agency (EPA) for various regions of the United States. Table 7 shows the amount of each chemical released in the SERC region, which includes the State of Georgia [20].

Table 7: EPA Pollution Data

Chemical	lbs/MWh
CO2	1490.0
CH4	0.02627
SO2	8.87
NOx	2.06

The PV system is expected to produce 4,698.7MWh of electricity during its 30-year lifetime. Table 8 shows the amount of emissions avoided after accounting for the 4.31 energy payback time.

Table 8: Estimated Emission Offset of the 152.5kW System

	Pollution from conventional electricity	Lifetime 4,698.7MWh	Yearly average of 156.6MWh
Chemical	lbs/MWh	offset in lbs	offset in lbs
CO2	1,490.0	7,001,063.0	233,368.8
CH4	0.02627	123.43	4.80
SO2	8.87	41,677.47	1,622.32
NOx	2.06	9,679.32	376.77

Future Studies

This study did not particularly deal with net-metering, which can be an integral part of any grid-connected PV system. However, future studies would examine recent advances in smart-grid technologies and their impact on distributed energy sources including the use of renewable energy. Further studies could also examine other design options such as taking time-of-use pricing for electric utilities and other considerations. Another expansion is to study the use of concentration lenses and ventilation methods to reduce temperatures, thus increasing the efficiency of PV systems.

The other aspect of this study is to bring renewable energy into education. For this purpose, a pre-engineering course is under development to incorporate student projects involving the use of a PV system to calculate efficiency as a function of solar irradiance and temperature. Future work would also involve using a prototype PV system to verify the theoretical results presented in this paper.

Summary

In this study, the feasibility of photovoltaic systems as a renewable energy source was investigated via a case study involving a shopping center. Several factors that went into the design process, including engineering, economic, and environmental aspects, were presented and discussed. The PV Watts method for estimating the energy production of the PV system was used to perform the financial analysis, including government and state incentives. Capital budgeting techniques were utilized to determine the net present value and internal rate of return based on estimated cash flows over a 30-year system lifetime. The market analysis provided techniques to predict the cost and performance of PV systems such as inverter lifespan, future inverter costs, and module degradation. These estimates, along with the expected trends in electricity costs, were incorporated into the cash-flow analysis to provide a more realistic solution. Design options to reach grid parity at certain government incentive levels were shown to provide optimal results. The environmental analysis conducted in this study takes into account the amount of pollutants avoided over the lifetime of the system as well as the time it takes to recover the energy that went into the manufacturing process.

Although PV systems are still expensive and not very efficient to use in this part of the country, they nevertheless offer valid long-term investment if uncertainties regarding fuel prices and environmental regulations are taken into considerations. Further studies involving smart-grid integration with distributed energy sources is suggested.

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