AC 2011-677: A VIABILITY STUDY OF PHOTOVOLTAIC SYSTEMS

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A Viability Study of Photovoltaic Systems

I. INTRODUCTION

The Industrial Revolution brought an enormous increase in the use of fossil fuels, specifically oil, coal and natural gas. The combustion of these fuels releases many gases such as carbon dioxide (CO2), carbon monoxide (CO), sulfur dioxide (SO2), nitrogen oxides (NOx), particulate matter, and lead[1] that are harmful to humans and the rest of the ecosystem. The additional CO2 released into the air by human activities is suspected to be a primary cause of what is known as global warming or climate change. Therefore, increasing energy efficiency and the use of renewable energy are herald as the most effective strategies to reduce air pollution and hinder anthropogenic climate change[2].

The sun is a major resource for renewable energy. By far, it is humankind's biggest energy resource, continuously delivering 120,000 terawatts to earth's surface. The use of solar energy can be divided into four main categories: passive solar heating, active solar heating, concentrated solar power (CSP), and photovoltaic electricity (PV). Passive heating refers to carefully designed buildings that let sunlight in during the winter, yet shade incoming sunlight during the summer. Active heating includes technologies that capture the sun's radiation for heating and cooling. Concentrated solar power refers to the use of lenses to concentrate solar energy for electricity or heating purposes[3]. PV devices make use of semiconductor capacity to convert sunlight directly into an electric current. Besides being renewable, PV systems are non-polluting, have no fuel costs, and have no rotating parts making them very reliable and long-lasting. Disadvantages of PV systems include a very large initial cost and low efficiency which requires a large number of panels to be installed in order to produce a substantial amount of electric power[4].

Two case studies were conducted to demonstrate the planning and designing of large PV systems. The first system involves a retail store called "MART" and the second involve a recreational center called "RAC". Designing aspect included engineering, economic, and environmental factors such as optimal array orientations, shading effects, and compatibility issues between the PV arrays and inverters under the forecasted weather conditions. Various methods for estimating the performance of a PV system were presented with the aim to determine if photovoltaic energy is both economical and environmentally sound, thus making it sustainable. Different capital budgeting techniques were also investigated to decide whether installing PV systems is financially feasible under the prevailing economic conditions. Finally, a term project involving the use of a small PV system is included in this paper to introduce pre-engineering students to renewable energy and its useful applications.

II. ENGINEERING ASPECTS

PV systems are classified under two categories: stand-alone and grid-connected (or utility-interactive). Stand-alone systems[4] are able to provide power while operating separately from the electrical utility grid. They are often found in rural or remote areas and use batteries to store energy since power production does not always coincide with the load demand. Grid-connected, on the other hand, are PV systems that function in conjunction with the electric utility. They can use the power grid to assist in meeting the demand of the loads when the PV system does not produce enough electricity. If the PV system sufficiently supplies the loads, excess solar power can be fed into the utility grid. Typically, this green energy is sold back to the utility for wholesale or retail value depending upon local laws and regulations. This type of arrangement is called net-metering[4]. Purchasing energy from PV generating systems typically depends on the size of the systems and residential or commercial use [5]. The main components for any grid connected PV system are the arrays, the mounting structure, the combiner box, and the inverter. An array is a collection of modules that are connected in different configurations. PV modules, commonly called panels, are a collection of PV cells that are connected in series and/or parallel combination and bound together on a common frame. A row of modules connected in series is called a series string or simply, a string. The combiner box contains several protection devices such as circuit breakers and combines the series strings into a single output. The inverter converts the DC power from the array into standard AC electricity.

Solar Radiation and Local Climate

Solar irradiation is the total amount of solar energy collected on an area over time. Solar irradiation is typically expressed in kWh/m2. At most locations on Earth, solar irradiation will peak around 1 kW/m2 every day around solar noon. Insolation is the solar energy that reaches the Earth's surface over the course of a day. It is usually expressed in kWh/m2/day. The solar energy and temperature information used for this study was obtained from the National Renewable Energy Laboratory (NREL) software[6] called "*PV Watts v.2*" based on analysis of the National Solar Radiation Data Base (NSRDB). This data is from the Typical Meteorological Year Two (TMY2) which was collected during the 1961-1990 time period[7]. While the calculations are based on historical data, the actual performance of any PV system may vary. However, the values would be accurate within 10 to 12% [8]. The solar insolation received for fixed arrays facing due south at various tilt angles is shown in Table 1.

TABLE 1: 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

Since the best of these three array angles changes throughout the year, it may be economical to mount the modules on an adjustable platform and adjust the tilt angle throughout the year. This arrangement would allow the array to be tilted at 32.3° during March, at 17.3° from April to September, and at 47.3° from October to February. This may result in about 7.2% increase in energy output.

Array Orientation

For any location on Earth, the sun's position in the sky is dependent on the latitude, the time of day, and the time of year. It can be defined by the solar altitude angle and the solar azimuth angle. The Solar altitude angle is the vertical angle between the horizon and the sun (which varies between 0° and 90°). The solar azimuth is the horizontal angle between the sun and a reference direction (usually due south in the Northern Hemisphere). Solar azimuth angle varies between -180° and +180°. A negative angle is used when the sun is to the west of due south, while a positive angle is used when the sun is to the east of due south. PV arrays should be oriented at a tilt angle that is close or equal to the local latitude. To optimize the system energy production for the summer, the array can be mounted with a smaller tilt angle[4]. In the Northern Hemisphere, declination varies from 0° to +23.5° during the summer half of the year. The average declination during this time is about 15°. Therefore arrays should be mounted at 15° less than the location's latitude if the goal is to maximize energy production during summer. The opposite is true for the winter; the optimal tilt angle is the locations latitude plus 15°. At solar noon, the sun is directly above due south. However, depending on the system needs throughout the day, it may be more desirable to face the array slightly different than due south. For example, if the energy demand is greater in the afternoon, it may be more appropriate to face the array southwest to produce more power later in the day.

The proposed sites for the PV installations are large facilities served by 3-phase, 480 volt feeders. The electricity-use for both centers are shown in Figure 1 and Figure 2 respectively and the cost per kWh over 12 months period is depicted in Figure 3.

Shading Analysis

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. 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 and any losses that may occur if the proposed site deviated from the optimal orientation defined at 32.3° tilt angle and 0° azimuth angle (due south). For example, a site with optimal orientation will have 100% efficiency if no shading occurs throughout the whole year.

Figure 1: The electricity-use of the MART Center

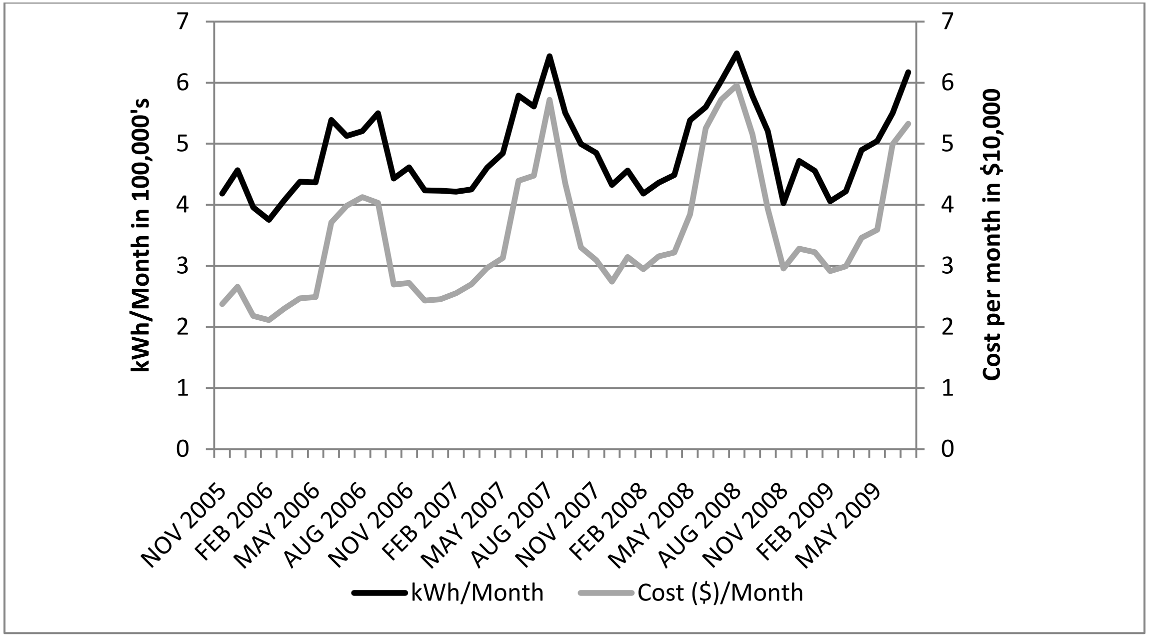


Figure 2: The electricity-use of the RAC Center

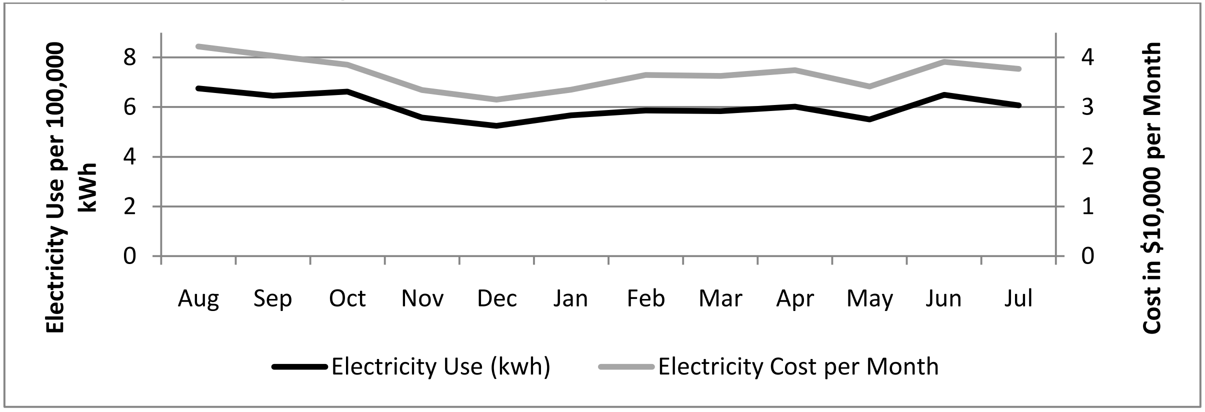
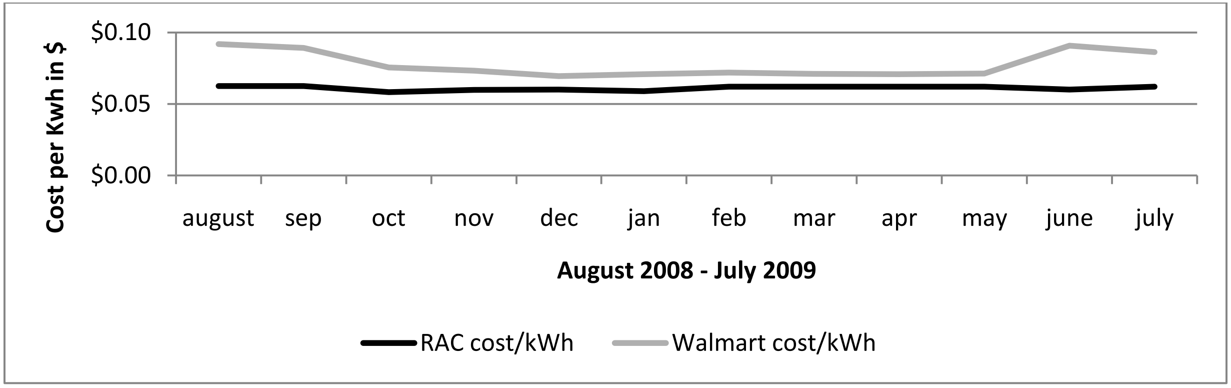


Figure 3: The Cost/kWh from August 2008 to July 2009



Three locations were identified for the MART center with the results shown in Table 3. As depicted, all three areas are considered excellent PV sites for their near optimal shading efficiency.

Table 3: Solar Pathfinder Evaluation of the MART Center

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

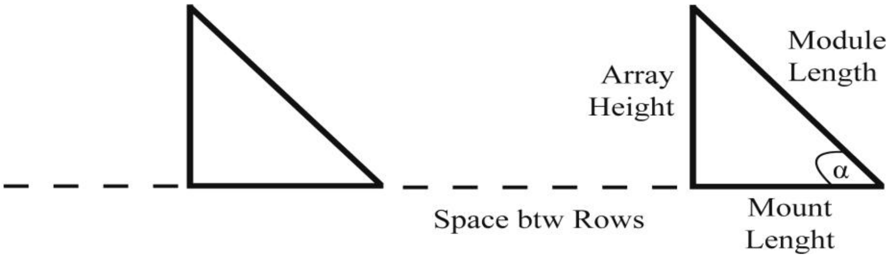
Similarly, a survey of the RAC facility concluded that several sites on the roof are suitable for PV installation. A total of six flat and sloped sections were examined using Pathfinder with the results shown in Table 4. Only three sites with efficiency above 96% were selected for further consideration. It should be noted that the sites are far away apart from each other making it necessary to divide them for separate PV systems.

Table 4: Solar Pathfinder Evaluation for the RAC Center

	Area	Tilt angle	Azimuth angle	# of samples	Site Efficiency
Flat roof area above pool	40.77m x 35.1m	0°	NA	4	98.21%
Flat roof area above offices	35.1m x 16m	0°	NA	4	98.1%
Flat roof area near entrance	21.35m x 16.76m	0°	NA	6	93.69%
Sloped roof on north side	36.7m x 10.3m	26.6°	10°	3	96.43%
Sloped roof east side	62.18m x 16.76m	18.4°	-80°	6	83.49%
Sloped center roof	82.3m x 17.68m	18.4°	-80°	5	83.51%

According to the building plans, the site on the northern side has a base of 10.3m and extends 36.58m with a slope of 6/12 that translates into 26.6° [12]. The PV space available is 11.52m x 36.58m as determined by the Pythagorean Theorem. While the local latitude is generally accepted as the ideal tilt angle[8] ,some sources recommend using a smaller tilt angle found either by subtracting 9° or 10% from the latitude which would result in 25.4 or 29.1 respectively[12] . Therefore, it is possible to mount the PV modules on this slope with no need for additional tilting. An equally important factor to consider is to minimize the module self-shading where rows cast shadows on the subsequent rows. This problem can be solved by ensuring that there is sufficient space between the module rows or by the often less favorable option of lowering the array tilt angle [4]. The spacing between the module rows is depicted in Figure 4.

Figure 4: Spacing Between PV Rows



As shown in the following formulas, the height of the array and the mount length can be found by the following formulas for any module length and angle α:

$$Array\ Height = \ Module\ Length\ x\ (\sin\alpha)\ Mount\ Length = Module\ Length\ x\ (\cos\propto)$$

It is reasonable to set minimum solar altitude angle when there is no shading from 9 AM to 3 PM[4] . For 32.3° N latitude, the sun has an altitude angle around 20° during the winter. Therefore, the minimum space between the rows denoted by *D* can be found from the following relationship:

$$D = \frac{Array Height}{(\tan 20^0)}$$

Therefore, all arrays rows must be separated by least 3.33m in order to prevent modules from casting shadows on in other as shown in 5.

Table 5: Calculations of Necessary Array Spacing

	winter	fall/spr	summer
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
min distance btw rows (m)	3.33	2.42	1.35
total space need for row (m)	4.45	3.82	2.92

Temperature Effects and Array/Inverter Compatibility

The electrical performance of a PV module is largely determined by the collected solar irradiance and the temperature of the cells in the module. The module's current is directly proportional to the collected solar irradiance, while module's voltage is inversely proportional to the temperature of the cells within the module. The temperature of the PV cells directly related to the ambient temperature, the amount of solar irradiance and the module mounting configuration. High cell temperatures substantially reduce the voltage of the module. The expected rise in cell temperature due to solar irradiance can be estimated by a temperature-rise coefficient (T_{rc}) typically given in °C/kW/m^2. The record high ambient temperature for Savannah is 105.1°F. Three of the four systems considered are designed with the modules attached to rack mounts while the other attached to standoff mounts. Rack mounts and pole mounts allow substantial air circulation resulting in a relatively low temperature-rise coefficient falling between 15 to 20 °C/kW/m^2 (27 to 36 °F/kW/m^2). Standoff mounts offer less air circulation and therefore have a suggested temperature-rise coefficient within the range of 20 to 30 °C/kW/m^2 (45 to 54 °F/kW/m^2). The cell temperature, T_{cell} at a given irradiance E and ambient temperature T_{amb} can be estimated by the following formula[4].

$$T_{cell} = T_{amb} + \left(T_{rc} \times E\right)$$

The performance characteristics and temperature coefficients for the *Evergreen ES-A-210 fa3* PV models used in this study are listed in Tables 6 and 7 respectively. The data is provided by the manufacturer under standard test conditions (STC) as explained in[9].

Table 6: STC of the ES-A-210 fa3

P_{MAX}	210 W
V_{MPP}	18.3 V
I_{MPP}	11.48 A
V_{OC}	22.8 V
I_{SC}	12.11 A
Minimum efficiency	13.40%

Table 7: ES-A-210 for 3 Temp. Coefficients

P_{MAX}	-0.43%/°C
V_{MPP}	-0.40%/°C
I_{MPP}	-0.03%/°C
V_{OC}	-0.31%/°C
I_{SC}	+0.05%/°C

The main electrical parameters of a PV module are the maximum power (P_{MAX}), maximum power voltage (V_{MPP}), maximum power current (I_{MPP}), open circuit voltage (V_{OC}), short circuit current (I_{SC}), and conversion efficiency, all of which are dependent upon the cell temperature and the solar irradiance. For these PV models, a voltage of 18.3V and current of 11.48A will produce maximum power 210W[4] expressed as:

$$P_{MAX} = V_{MP} \times I_{MP}$$

Temperature coefficients are used to approximate the rate of change in the voltage, current, or power output of a PV module as its cell temperature deviates from the standard test condition (STC) of 25°C. The maximum power voltage, V_{MPP}, open circuit voltage, V_{OC}, and short circuit current, I_{SC}, for any cell temperature can be found by the following formulas [4].

$$V_{MPP} = \left[1 + \left(T_{cell} - T_{STC}\right) \times T_{\%V}\right] \times V_{MPP(STC)}$$

$$V_{OC} = \left[1 + \left(T_{cell} - T_{STC}\right) \times T_{\%Voc}\right] \times V_{OC(STC)}$$

$$Isc = \left[1 + \left(T_{cell} - T_{STC}\right) \times T_{\%Isc}\right] \times I_{SC(STC)}$$

PV systems should be 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 maximum power point tracking (MPPT) circuits to ensure the array always produces maximum power under varying cell temperatures and solar irradiance. The maximum number of modules, in a string can be found by the quotient of the maximum 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[11].

System Sizing

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 always greater than 1 for two main reasons: 1) modules rarely operate at STC conditions; and 2) inverters cannot have an output greater than their nominal value. An inverter ratio around 1.15 is common in the PV industry[10] . When a system has an inverter sizing ratio higher than 1.3, there will be significant energy losses, and premature aging of the inverter[11]. 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 efficiency around 98% is less sensitive to variations in the inverter sizing ratio [13].

Using the methods described in the previous sections, four PV systems are designed and discussed in this paper. A potential system designed for the MART site is a 286.4 kW system. For the RAC site, three PV systems with total DC generating capacity of 97.23 kW were proposed for the roof as follows: pool area (35.28 kW), offices area (13.44 kW), and the sloped area (48.51 kW).

The results of the calculations used to size each PV system are presented in Table 8. Special care was taken to ensure that these sites are large enough to accommodate each system. Requests for a layout of each system can be fulfilled by contacting one of the authors.

Table 8: PV System Sizing Calculations

	MART Center	RAC Pool	RAC Ramp	RAC Offices
Hottest Day (°C)	40.6	40.6	40.6	40.6
Coldest Day (°C)	-16.1	-16.1	-16.1	-16.1
temp rise coef (°C/kW/m^2)	20	20	30	20
max solar irradiance (kW/m^2)	1.3	1.3	1.3	1.3
module temp at hottest day	66.6	66.6	79.6	66.6
Inverter Models	SC250U	Satcon 30	Satcon 50S	Sol PVI 13
Nominal AC output	250	30	50	13.2
max input voltage	600	600	600	475
maximum MPP voltage	600	600	600	380
minimum MPP voltage	330	295	265	205
max DC input current	800	104	198	64
Inverter Efficiency	97.0%	95.0%	95.5%	95.8%
Voc at coldest temp	25.70	25.70	25.70	25.70
max power at hottest temp	15.25	15.25	14.30	15.25
Isc at hottest temp	12.36	12.36	12.44	12.36
string Voc at coldest temp	565.5	539.8	539.8	411.2
string max power at hottest temp	335.6	320.4	300.4	244.8
max # of series connected modules	23.3	23.3	23.3	18.5
min # of series connected modules	21.6	19.3	20.6	13.4
# of modules in series	22	21	21	16
max # of strings	64.72	8.41	15.92	4.85
# of series strings	62	8	11	4
total # of modules	1364	168	231	64
inverter sizing ratio	1.15	1.18	0.97	1.02

In order to collect maximum solar energy, PV modules should ideally be facing the sun at all time. This can be achieved by using a sun-tracking system that automatically orients the array to the position of the sun. This would result in an annual energy increase up to 40% over rack mounted systems[12] . However, sun-tracking is usually used for smaller applications and rarely roof mounted which may cause structural problems[14]. In this study, rack systems made by IronRidge were used with mount models UNI-GR/12H and UNI-GR/14H capable of holding 7 and 8 PV arrays respectively.

III. SYSTEM PERFORMSNCE

Two methods to estimate the performance of PV system are discussed in this section. One is based on the "*PV Watts v2"* program developed by NREL and the other method makes use of a basic formula for direct system calculations. NREL suggests common values for the various losses associated with PV systems. These are shown in Table 9 and utilized here except for the inverter and shading which use the actual inverter efficiency and measurements from the Solar

Pathfinder analysis. According to NREL, PV modules should be derated by 1% each year after installation[15] .

Table 9: Derate Factors used for Walmart Calculations

Component Derate Factors	PV Watts Default	NREL suggested Range	MART 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 availability	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

PV *Watts's* v.2 Method

As mentioned earlier, this analysis is based on a program developed by NREL [6] using typical meteorological year (TMY) weather data and PV performance model. The results based on a DC power rating of 286.44 kW are shown in Table 10.

Table 10: MART Energy Analysis by PV Watts v2

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

Direct Calculation Method

This method determines the amount of energy E, produced by a PV system as:

$$E = \#\ of\ modules \times module\ rating\ \times solar\ insolation \times number\ of\ days \times derate\ factor$$

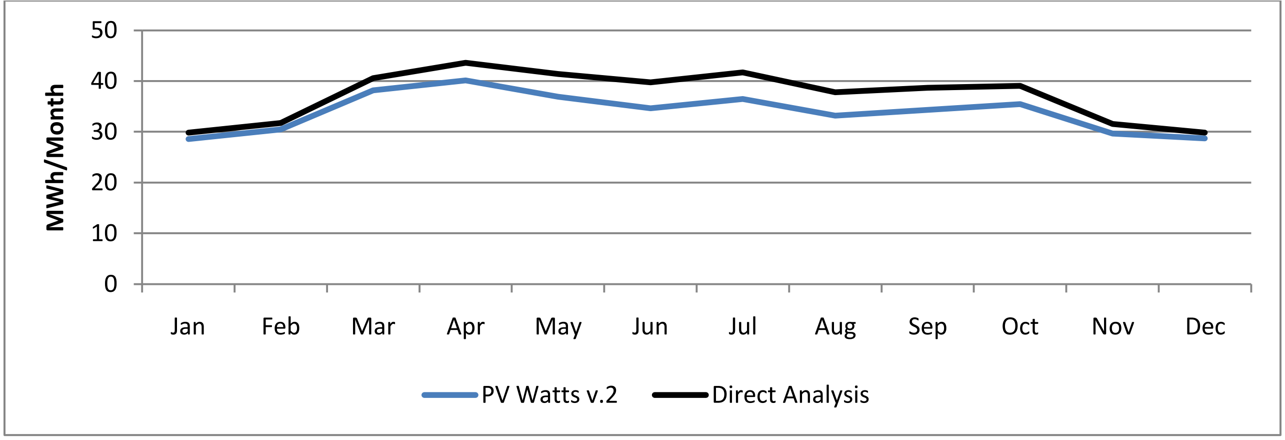
The results of the calculation with a derate factor of 0.806 are shown in Table 11.

Table 11: MART Energy Analysis using Direct Calculation

	$/kWh	days	Insolation (kW/m2/day)	kWh produced	$ value
Jan	0.0708	31	4.17	29,845	$2,113.00
Feb	0.0718	28	4.91	31,740	$2,278.94
Mar	0.071	31	5.67	40,580	$2,881.19
Apr	0.0707	30	6.29	43,565	$3,080.07
May	0.0713	31	5.78	41,367	$2,949.50
June	0.0908	30	5.74	39,756	$3,609.84
July	0.095	31	5.83	41,725	$3,963.90
Aug	0.0919	31	5.28	37,789	$3,472.80
Sep	0.0891	30	5.58	38,648	$3,443.51
Oct	0.0755	31	5.46	39,077	$2,950.33
Nov	0.0733	30	4.55	31,514	$2,309.96
Dec	0.0695	31	4.17	29,845	$2,074.20
total		365	5.29	445,451	$35,127.24

The result comparison in Figure 5 revealed that both methods predict similar results from November to February, but the *PV Watt v2* method produced less energy during the warmer months of the year. This is expected due to the fact that the output power of PV systems is reduced at higher temperature. The direct calculation method, on the other hand, did not capture that since it does not take weather data into account.

Figure 5: Comparison of *PV Watts v2* and *Direct Calculation* Results



IV. FINACIAL ANLYSIS

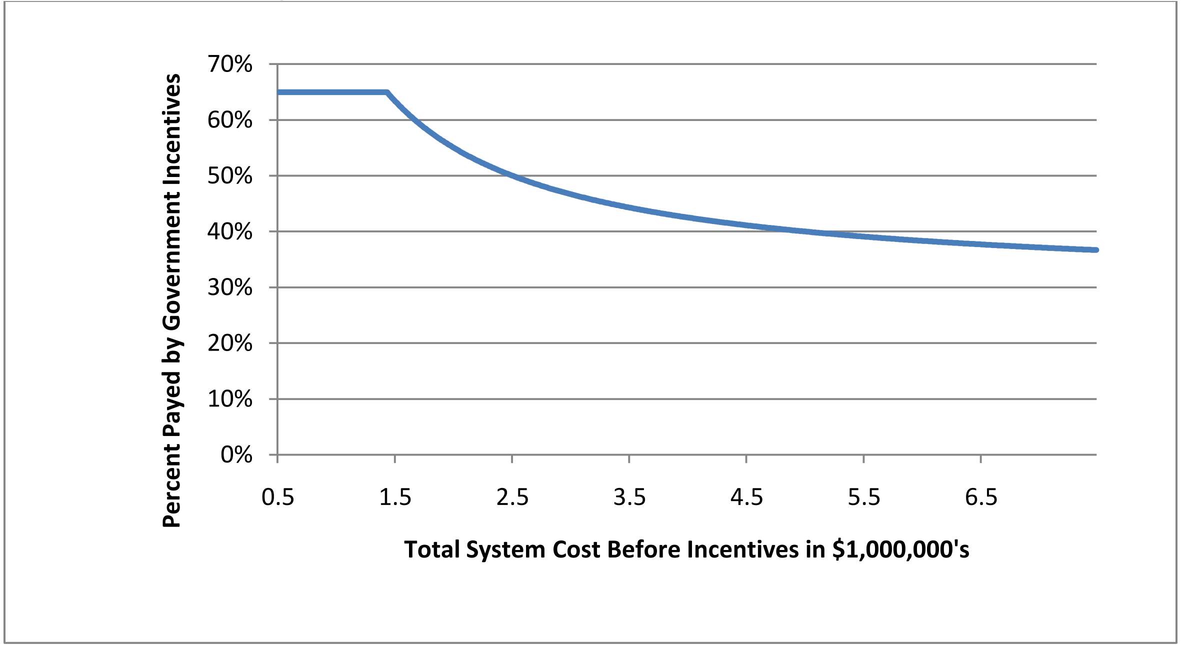
The financial analysis conducted here and shown in the appendix was based on Brigham and Ehrhardt's capital budgeting methods [16] with cash flows estimated for the lifetime of the PV system. A detailed description of this analysis including government incentives is given next.

The federal government, along with many State and local governments in the United States offer financial incentives for the purchase of renewable energy systems. Since the MART center is a private and the RAC is part of a public university, they are qualified for different incentives. The federal government offers many incentives under the American Recovery and Reinvestment Act of 2009 (H.R.1). Furthermore, the Business Energy Investment Tax Credit (ITC) offers a corporate tax credit of 30% up to the full cost of PV systems. As a tax paying corporation, the MART center is entitled for this tax credit but the RAC is not qualified [17].

The state Clean Energy Tax Credit offers 35% corporate tax credit of up to $500,000. Therefore the largest system to receive this tax credit must not cost more than $1,428,571. However, this tax credit which became effective 7/1/2008 is going to expire by 12/31/2012[18] . Therefore, a $1,428,571 PV system could be installed costing only $500,000 or 65% of the original cost.

Additionally, the state offers the Clean Energy Property Rebate Program which covers 35% of the cost of PV systems up to $500,000. Commercial businesses, nonprofit organizations and schools qualify for this rebate and would work very well for the RAC. Unfortunately, this program has received applications exceeding its allocated fund[18] . The effect that the total cost of a PV System has on the amount paid through these various incentives is shown in Figure 6.

Figure 6: Government Incentives Available for PV Projects



A review of the literature found 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% and 7% [21] may be used for financial analysis. Module degradation rates may vary between .5% and 1.0% per year [15]. PV modules have life expectancies of up to 40 years[12] but inverters need to be replaced every 5 to 10 years [22] . The price of inverters is expected to decrease by 35% in 10 years and by 50% in 20 years [22]. The weighted average cost of capital for the MART center is around 7.04% [23] and an appropriate discount rate for PV systems is 4% to 6% [24]. A study conducted in 2008 by the Lawrence Berkeley National Laboratory[20] set the average cost of rack-mounted PV systems (>100kW) to $7.20 per installed watt capacity or $7.28 in today's dollars [20]. At this rate, the price of the 286.44 kW system that MART can accommodate is $2,085,283 but it would actually cost $959,698 after the 30% federal tax credit and the 35% state tax credit. Therefore, instead of 65%, the only 54% of the total cost is paid through government incentives.

The sensitivity analysis gives insight on how the net present value (NPV) of a given investment would change if the assumptions that went into the calculations were different. A positive value indicates a profitable investment while a negative value indicates a loss. The sensitivity analysis for the MART center under the (*PV Watts v.2*) method is depicted in Figure 7 and based on a yearly electricity price inflation of 6.7%, module degradation of 1.0% per year, 30 year system life with inverters replaced every 10 years, and a 7.0% capital cost.
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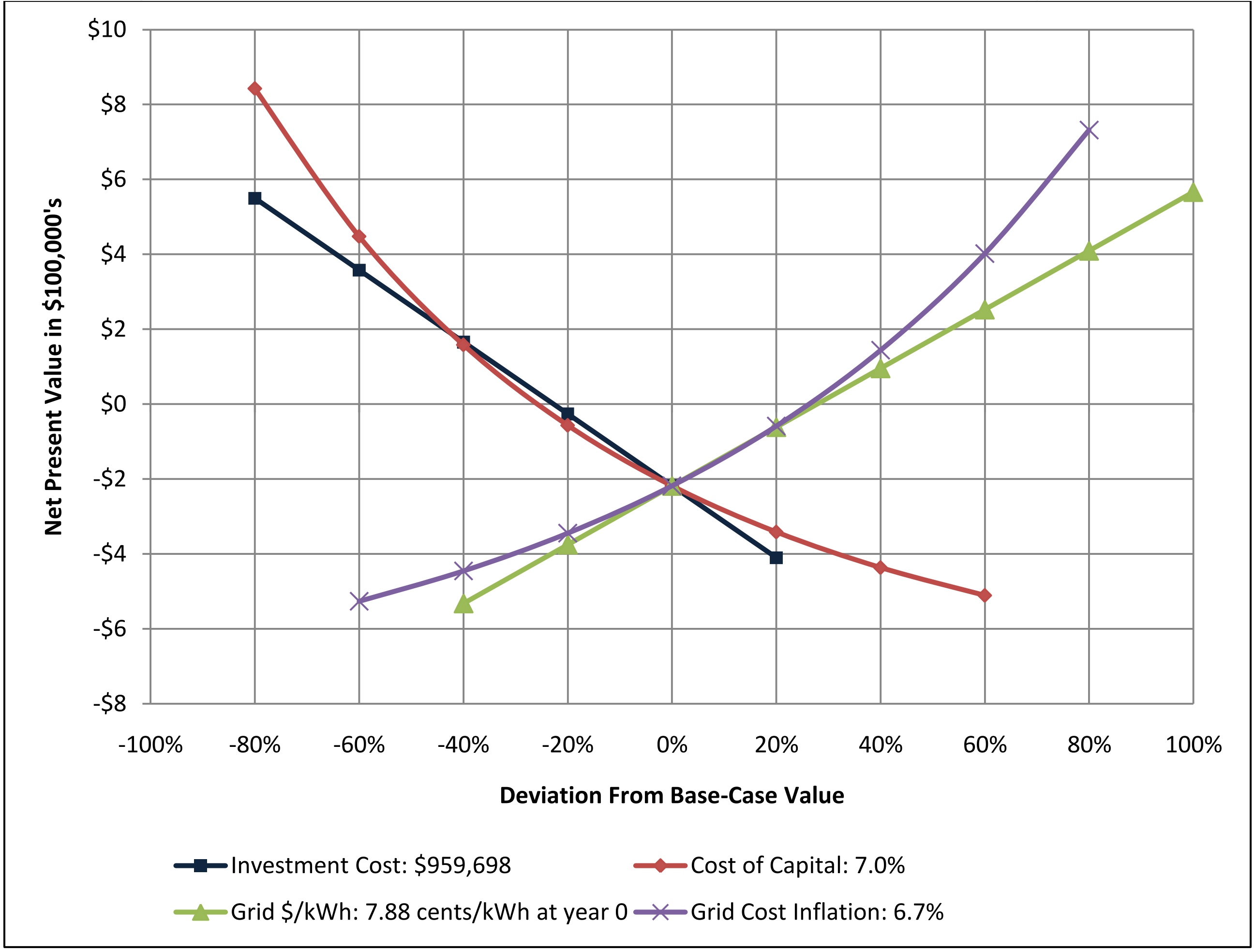
Figure 7: Net Present Value VS. Base-Case Deviations for the 286.4 kW System



In the base-case scenario for the 286.4 kW system, the NPV and the internal rate of return (IRR) were found to be -$218,214 and 5.19% respectively. Therefore, the project return is not sufficient to cover the cost of capital even after all the government incentives were utilized. The fact that the NPV is negative suggests that photovoltaic systems of this size have not reached grid-parity in this part of the country. Grid-parity is the point upon which the cost of photovoltaic electricity is equal to or less than the price of grid electricity[25]. The state average electricity price of 8.44 ¢/k which is considered relatively low compared to the rest of the country. Many other states have much higher costs for electricity[26]. Due to the large system size, the state tax credit on the 286.4 kW system would amount to $500,000 which is only 24% of the total cost. Therefore, instead of 65%, only 54% of the total cost is paid through government incentives. Further analysis indicated that the PV system could reach grid parity when government incentives cover at least 64.4% of the cost. Thus, a 196.2 kW PV system will harness all the available incentives making the investment more attractive.

In practice, PV energy production may vary by 12% which can significantly impact the results of the financial analysis. For this purpose, 3 more cases were analyzed assuming 12% deviations and the energy calculation using the direct method. It should be noted that the NPV and IRR for the direct method estimation were found to be -$92,400 and 6.25% respectively- a more attractive scenario since a positive NPV can be achieved at initial electricity cost of 8.7 ¢/kWh. Consequently, it is unlikely that the PV systems designed for the RAC center will produce a positive NPV since it will not qualify for any financial incentives and currently pays about 22% less for the price of electricity than the MART center. However, PV systems installed on colleges and universities are mostly funded to conduct basic research and for educational purposes without much emphasis on financial profitability.

V. 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 produce the amount of energy that went into manufacturing the components is called the energy payback per years EPB given as:

$$EPB = \frac{Eman}{Esun \times \eta}$$

Where:
$Eman$ is the manufacturing energy
$Esun$ is the receivable solar energy in kWh/m^2/year, and
η is efficiency of the PV module

The Evergreen ES-A-210 module, made from multi-crystalline silicon has a minimum efficiency of 13.4% and requires no more than 650 kWh/m^2 of energy to manufacture [27]. In Statesboro, the received solar energy is about 1932 kWh/m^2/year[6]. 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 systems are 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 12 shows the amount of each chemical released in the SERC region which includes the state of Georgia[28].

Table 12: EPA Pollution Data

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

The 286.4 kW PV system designed for the MART is expected to produce 10,370 MWh of electricity during its 30 year lifetime. Table 13 shows the amount of emissions that the PV system could offset after accounting for the 4.31years energy payback time.

Table 13: Estimated Emission Offset of the MART Center

	Pollution from conventional electricity	Lifetime 8880 MWh	Yearly average of 296.0 MWh
Chemical	lbs/MWh	offset in lbs	offset in lbs
CO2	1490.0	13,231,647.0	441,040.0
CH4	0.02627	233.29	7.78
SO2	8.87	78,768.26	2,625.52
NOx	2.06	18,293.42	609.76

VI. STUDENT PROJECT

The student project was developed to introduce students to renewable energy making use of a PV system connected to the internet via a data acquisition system. The sensors installed on the system measure temperature, wind speed, solar irradiance, and electric energy produced. Students were asked to collect and analyze the data to determine efficiency and amount of pollution prevented. The following is a project performed during fall 2010 semester.

1. Project Objectives

- To collect data about solar irradiation and site temperature
- To calculate efficiency of the PV photovoltaic system

2. Equipment Used

Equipment	Description	Comments
Lab Solar Photovoltaic System	Model SW115 115 Watt 12V	1.87 m^2 Total Area

3. Procedure

3.1. The following data was used for calculations:

3.1.1. Solar Irradiance = 1000W/m^2 (standard solar efficiency at 25° C).
3.1.2. NREL estimates Georgia solar irradiance at 208W/m^2.
3.1.3. PV module Area: 2 x (56.93 in x 25.43 in) for Model SW115 115 Watt 12V.
3.1.4. Power = Voltage x Current.
3.1.5. Module standard efficiency = rated power / (1000 x Area).
3.1.6. Module Actual Efficiency = power recorded / (Site irradiance x Area).

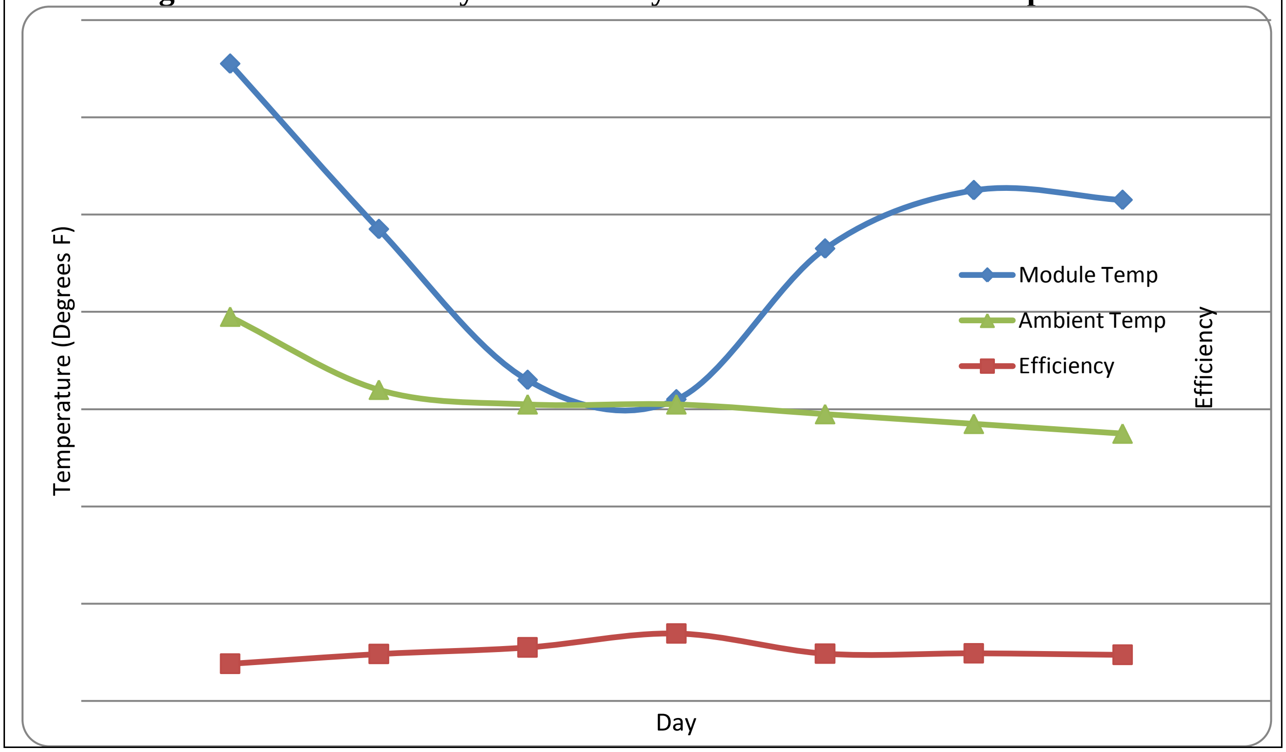
4. Results

The results are shown in Table 14 and plotted in Figure 8.

Table 14 – Solar Energy Data from Data Logger and Calculated Efficiency

Day	Power (V x A)	Ambient Temperature (F)	Module Temperature (F)	Solar Irradiance	Efficiency % (Calculated)
1	78	79	131	544	7.67
2	169	64	97	934	9.68
3	39	61	66	189	11.03
4	26	61	62	100	13.90
5	176	59	93	964	9.76
6	182	57	105	990	9.83
7	172	55	103	967	9.51

Figure 8 – The Efficiency of the PPV system as a Function of Temperature.



4. Questions:

- **What is the efficiency of the 115 W module under standard conditions?**

  Module standard efficiency = rated power / (1000 x Area)

  Area = 2 x (56.93 in x 25.43 in) = 2,895.5 in^2 x 6.4516 x 10^{-4} m2 / in^2 = 1.87 m^2.

  Module standard efficiency = 115 W / (1000 x 1.87 m^2) x 100 = 61.5%

- **What is the power produced if the irradiance sensor reads 860 W/m^2?**

  Module Actual Efficiency = power recorded / (Site irradiance x Area)

  Power = Module Actual Efficiency x (Site irradiance x Area)

  Power = Module Actual Efficiency x (860 W/m^2 x 1.87 m^2)

- **Does the temperature have an effect on efficiency?**

  Yes, the temperature of the module and the efficiency are inversely proportional

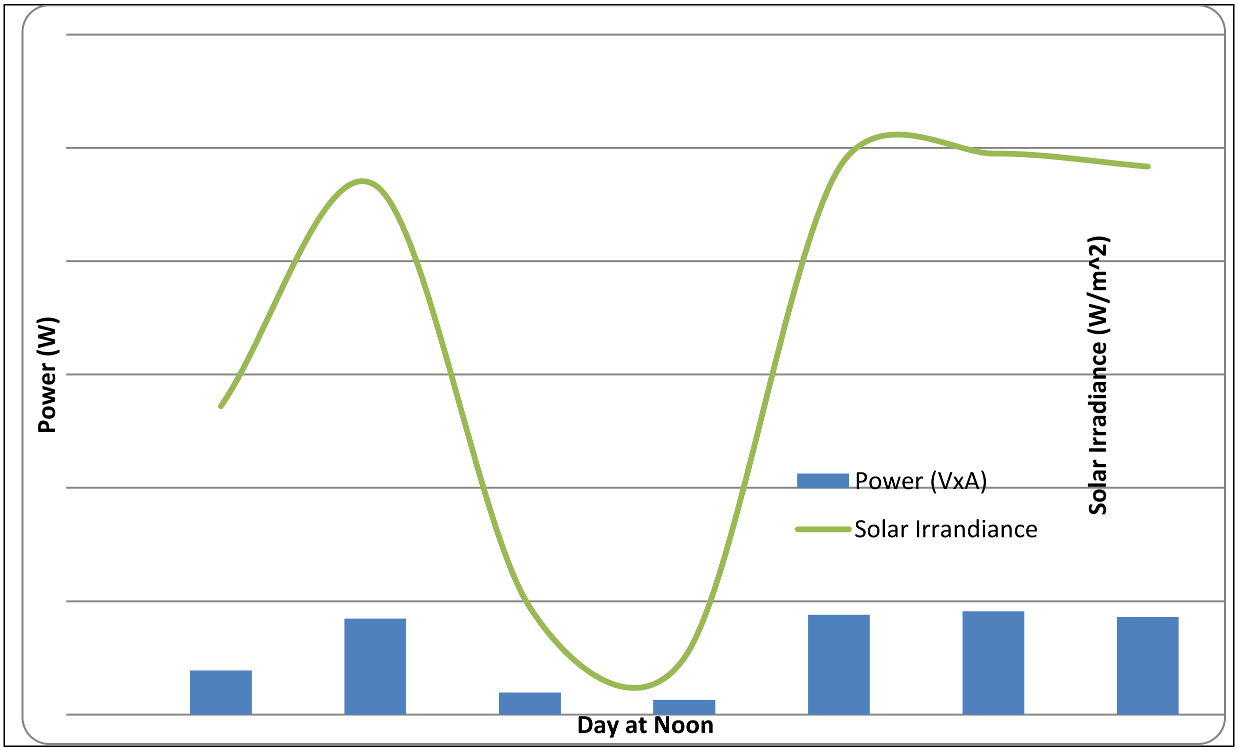
- **Give some ideas on how to increase the efficiency of the system.**

  Increased airflow around the unit might net an increase in efficiency. If greater cooling were needed, a liquid could be used to cool the module. The heated liquid could then be circulated to a heat exchanger and used to provide hot water or other useful purpose.

5- Observations

From the data collected, it appears that solar irradiance has the greatest effect on the power generated by the PV system as shown in Figure 9.

Figure 9 - PV Power Generation as a Function of solar radiation



From the weekly voltage and current data, it appears that the solar irradiance has less impact on the voltage generated than it does on the current generated.

VII. CONCLUSIONS

Concerns over climate change and other environmental problems highlight a need for a shift to clean and renewable energy. The main objective of this study was to investigate the viability of photovoltaic electricity in the southeastern region of the United States. To achieve this goal, two case studies were conducted involving a large retail store and a recreation center. Historical data related to weather conditions, solar energy and power demand were investigated and as a result grid-connected photovoltaic systems were designed to provide green energy for these facilities. Several engineering factors that went into the design process as well as economic and environmental considerations were discussed in this paper. Although a PV system does not emit any pollution, manufacturing its components require a substantial amount of energy. Thus, a realistic study must take into consideration the energy payback period in addition to the pollution offsets of the PV system. The engineering analysis dealt with factors such as solar radiation, shade evaluations, array orientation, module string sizing, and estimating energy production. The economic analysis used capital budgeting techniques to determine the net present value and internal rate of return based on estimated cash flows over the lifetime of the system. The market analysis considered various assumptions related to the cost and performance of PV systems such as inverter lifespan, inverter costs, and module degradation. These assumptions, along with the future trends in electricity costs, were incorporated into the cash flow estimates.

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

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