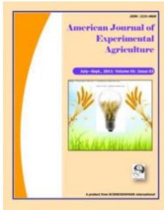

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An Outline for Economical and Technical Analysis of Solar Panels for Agricultural uses: A Case Study on Texas Weather Conditions

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Authors' contributions

DL, constructed the solar panels stands, configured the data recorded, and performed experimental work.JP performed experimental work, data analysis and wrote the first draft of the manuscript and SC designed the study, managed the analyses of the study and supervised the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To outline the necessary steps in the evaluation of solar panel systems in agriculture.
Study Design: Using the outline proposed, GaAs and Si solar panels were evaluated under central Texas weather conditions.
Place and Duration of Study: Bioenergy Testing Laboratory (BETALab) between January and August 2013 in College Station, Texas.
Materials and Methods: The study includes an outline on how to do a technical and simple economic comparison between solar panels. The outline includes the solar panel efficiency, required area, installations and power generation costs and simple payback period. To exhibit the application of the outline, two different photovoltaic systems were compared (silicon (Si) PV panels and the gallium arsenide (GaAs) PV panels). The solar panels were compared simultaneously, taking measurements of voltage and current automatically in College Station, Texas.

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Results: The GaAs solar panel showed conversion efficiency (18.36%) higher than Si panels (14.02% Si); however, it also has a capital cost ($3/Wp) higher than Si panels ($2/Wp). The study suggested that both panels are viable alternatives for energy independence in a small farm or ranch application. The final selection will depend on the economic alternatives and power necessities of the farmer or rancher. In this study, the GaAs have provided less payback period (6.8 years) compared with 7.5 years for the Si units using various assumptions. The larger efficiency of the GaAs (4%) unit translated into a better payback period despite its higher initial installed cost.
Conclusion: The technical and economical outline proposed in this paper was useful to decide between GaAs and Si panels using basic economic assumptions. However, this paper did not recommend a specific solar panel over the other in every situation. Each situation needs to be analyzed individually taking in consideration geographical situation, government subsidies, rebates and tax credits.

Keywords: Economic analysis; technical analysis; gallium arsenide photovoltaic panels; silicon photovoltaic panels; efficiency.

1. INTRODUCTION

The energy potential in Texas is one of the largest in the United States, with abundant wind, solar, and biomass resources in different regions across the state. In 2010, the renewable energies in Texas accounted 3.9% of the total energy consumed in the state. From the renewables energies used in the U.S., solar energy was responsible for 2% of the renewable energy total in 2011 [1]. Besides this low percentage, the solar energy industry is growing rapidly, example of that is the growing in 2010 (29%) and 2011 (25%) [1]. The state of Texas is ranked nationally as No. 1 in solar energy potential and No. 13 in installed solar photovoltaic capacity [2]. The large potential that the state of Texas possesses for solar energy opens many opportunities to develop new types of technologies and improve conventional ones.

In Texas, agriculture is one of the most important industries being the No. 1 state for total livestock and livestock products receipts, and the No. 2 state for agricultural receipts [3]. This high agricultural production is related with economical expenses which are principally connected with water, chemicals, and energy consumption. The energy consumption in a cattle farm in one year can be between 200 kWh/cow and 600 kWh/cow, this calculation is made by adding the total number of kWh units used in a year and divided it by the number of cows in the ranch [4]. The energy expenses can be reduced in the agricultural practices by the usage of solar energy as principal energy resource or as a supplementary source. The implementation of solar energy as power source in an agricultural system is a possibility for Texan farmers because the high solar potential and the federal and state benefits allow the implementation of this technology [1].

Solar panels can be applied in agriculture for water pumping, lighting, irrigation, aeration, electric fencing, ventilation, greenhouse production and building needs [5-7]. Additionally, farmers have great opportunities to be favored for the solar energy in terms of governmental benefits and environmental and economic revenues. However, they need to select the best type of solar technology that best fits their economic necessities. In that way, this paper outlines the necessary steps to perform a technical an economic evaluation of photovoltaic solar panels. This outline can be used as a tool by agricultural and biological engineers, Agricultural Systems Management or another agriculture related profession around the world without need of extensive knowledge in the operation of photovoltaic solar panels.

As example of the implementation of this outline; in this paper, two types of photovoltaic panels were evaluated. PV panels are glass covered semiconductor panels which can convert sunlight directly into electric energy. The PV panels can be produced from different materials, generating different characteristics, advantages, and prices [8]. The traditional PV panels have been formed using crystalline silicon, a less expensive material with reasonable performance [9]. Today, new PV panels have been developed trying to achieve higher efficiencies than silicon PV panels. The Gallium Arsenide (GaAs) solar panel is recognized as a very efficient panel [9]; however, the material prices make GaAs more expensive than traditional silicon. The differences in performance and price of these two panels are clear. However, before make a selection between these solar panels; it is necessary to perform economic and technical studies that take under consideration the weather conditions, the location and the power necessities.

The principal aim of this research was to outline the steps in the technical and economical evaluation of solar PV systems, comparing GaAs and Si solar panels under Texas weather conditions.

2. MATERIAL AND METHODS

2.1 Solar Panels Configuration

The experiment was performed using three commercial Silicon (Si) (0.9××0.28 m) and two Gallium Arsenide (GaAs) panels (0.59×0.59 m) donated by USDA-ARS, in Lubbock, Texas. The panels' configuration (Fig 1.) was developed to create identical testing situations for both panels under temperatures between 29 and 33 °C. The panels were mounted on separate rolling platforms, both at the same distance from the ground and tilted at an angle of 35 degrees from the horizontal. The angle used in this research corresponds to the original angle of the commercial Si solar panels. To obtain the closest conditions between both solar panels, the surface area of one of the Si panels was covered to match the surface area of the GaAs panel. After the adjustments the final exposed area for each solar panel was 0.6975 m^2.A research-grade pyranometer (CMP 22, Kipp and Zonen) was used to measure the input solar irradiance (W/m^2) that the panels were exposed to. The pyranometer was placed near the panels and tilted at the same 35 degree angle as the solar panels. During experimentation the panels were placed in the same location inside the Texas A&M campus. All data were recorded on an Omega 320 data logger (Omega Engineering Inc., Stamford, Connecticut). The logger was programmed to record and calculate the current, solar irradiance, power output and efficiency of both panels simultaneously taking points each minute. The data logger and the pyranometer used in this research were previously acquired by the laboratory for other researches.

2.2 Solar Panels Efficiency

To calculate the efficiency of the panels, it is necessary to know the irradiance, the power output and the surface area. The irradiance was measured by a pyranometer in W/m^2. To calculate the power output of the panels, a resistor was connected into the panel's circuit to induce a current. The resistor had a known constant resistance and the voltage was recorded across the resistor. According to Ohms law $V=I\times R$, the current was calculated from the measured voltage and known resistance (15 ohms). Once current was calculated, Watt's law (Power = $I\times V$) calculation yields the power output of the panel with the given resistance.

The power output from the panel is divided by the product of the irradiance and solar cell area to calculate the efficiency of the unit. Note that for the solar PV to operate under maximum power output at all times, the product of current (or amperage) and voltage must be at its maximum. Thus, the first sets of tests were made to determine the open circuit voltage (V_{oc}) of both the GaAs PV cell and the Si cell as solar irradiance varies throughout the day. This will establish the maximum output voltage as a function of solar irradiance. Unfortunately, during actual operation, current could not be measured if there is no load for the system hence, the set-up where a fixed or varying load is necessary. This may be done by varying the resistance across the load.

The short circuit current (I_{sc}) was established for each system and the maximum current drawn from each system is determined under varying solar irradiance. Thus, with the short circuit current known as well as the open circuit voltage, the maximum power output may be estimated or measured since a solar cell may operate over wide ranges of voltages and current. Under ideal scenario, maximum power output could always be achieved, with proper combination of current and voltage, or in this case, by adjusting the load for the solar panel. In actual ideal applications, the solar PV panels are exposed under the sunlight and are used to charge a battery using a MPPT which generates the combination of current and voltage that would generate the maximum power, while the load is simply connected to the battery during usage. This configuration will achieve optimum utilization of energy and power from the sun. In this research, a fixed load was used to show how to perform the technical and economic analysis of solar panels using basic conditions.

The calculation of efficiencies for this study was based on the maximum combination of current and voltage to achieve maximum actual power from each PV unit as shown in Equation 1.

$$\eta = \frac{P_m}{A_c \times S} \times 100\% \quad (1)$$

Where, η=solar PV panel efficiency, %, P_m=maximum power point, Watts, A_c= area of solar collector, m^2 (0.6975 m^2 in this study), S=incident solar irradiance on the collector, W/m^2. P_m is the maximum power output that could be generated at a given incident solar irradiance. This value will change according to the open circuit voltage and the current. In that way, at a given incident solar irradiance, the output voltage maybe projected and the proper load may be adjusted to generate the maximum power. Electronically, this is simply done by varying the resistance or the resistive load.

2.3 Solar Panels Economical Evaluation

To develop an economic comparison between the two solar panels, a simulation of the yearly performance of each solar panel was done. In this case, the environmental conditions used corresponded to College Station, Texas; Latitude (ϕ): 30.6°, Longitude: 96.3°, Solar Constant (G_{sc}): 1367 W/m^2, and Panels slope (β): 35°. The consumption assumed was a small cattle farm with 10 to 40 animals. Using 40 cows and supposing that each cow consumes 300 kWh/year [4], the farm will consume 1000 kWh/month. The efficiency of the systems was calculated using the experimental data and the life of systems supposed was 20 years. The economic assumptions used for the economical simulation are shown in Table 1. Balance of system includes all additional cost to have the unit in full operation such as the batteries, converters, controllers, wiring and other switches.

To make the comparison between the two solar panels it is necessary to calculate the daily revenue (D_R) using equation 2:

$$D_R = P_{day} \times grid \quad (2)$$

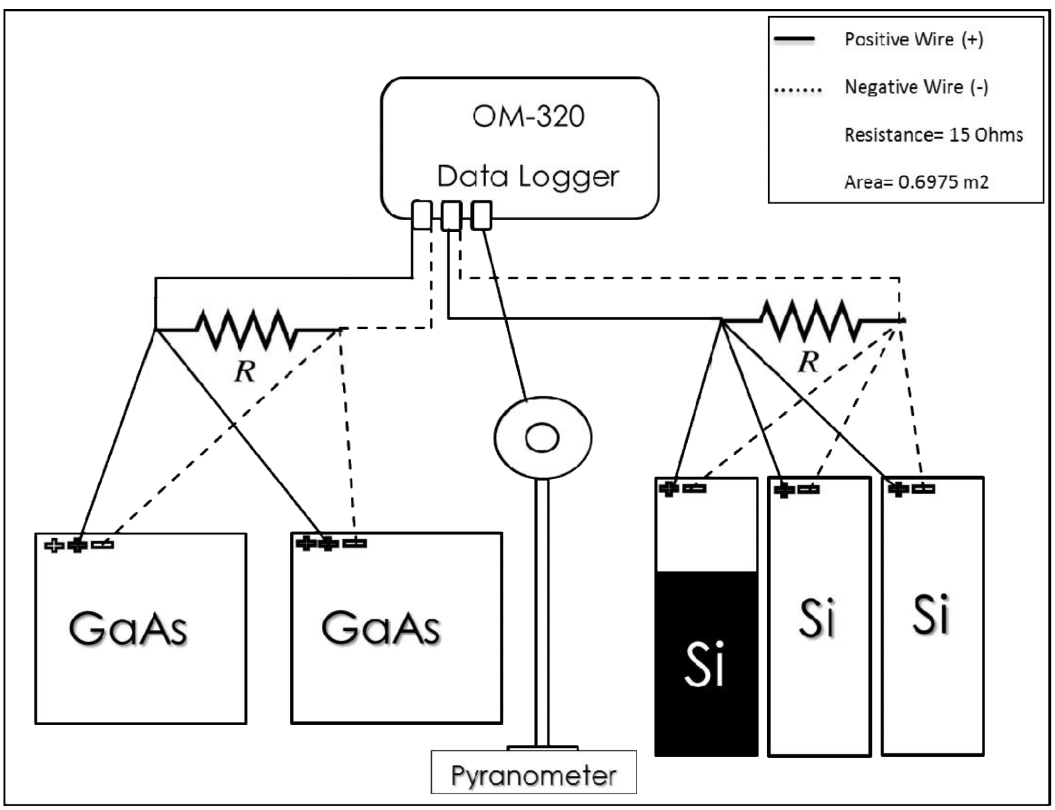


Fig. 1. Experimental circuit used in the solar panels data acquisition. The black colour in the Si panel represents the covered area

Table 1. Economic assumptions

Variable	Costs (Dollars)
Gallium Arsenide panels costs	\$3/Wp
Silicon panels costs	\$2/Wp
Gallium Arsenide system cost (Balance of system included)	\$7/Wp
Silicon system cost (Balance of system included)	\$6/Wp
Grid	\$0.12/kWh

Where *grid*= Cost of the energy in dollars/kWh, P_{day}= power generated by day kWh. P_{day} is calculated using the next equation:

$$P_{day} = \frac{A_c \times S \times \eta \times N_h}{1000} \tag{3}$$

Where A_c=solar panel area, m^2, S=incident solar irradiance, W/m^2, η=solar panel efficiency, N_h= number of daylight hours, h. N_h was calculated using equation 4 and S was calculated using the equation 6:

$$N_h = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) \tag{4}$$

Where ϕ is the Latitude, and δ is the declination angle. The declination angle is calculated using the equation 5:

$$\delta = 23.45 \times \sin\left(360 \times \frac{284 + n_d}{365}\right) \tag{5}$$

In equation 5 n_d correspond to the day of the year which is simulated from 0 to 365. The incident solar irradiance was calculated using the next equation:

$$S = H_0 / N_h \tag{6}$$

Where H_0= daily solar irradiance number, MJ/m^2 and N_h= number of daylight hours, h. To obtain the solar irradiance units (W/m^2) is necessary to use conversion factors in the formula. The daily solar irradiance number is calculated using equation 7.

$$H_o = \frac{24 \times 3600 G_{sc}}{\pi}\left(1 + 0.033\cos\frac{360nd}{365}\right) \times \left(\cos\emptyset\cos\omega_s + \pi\omega s 180 \sin\emptyset\sin\delta\right. \tag{7}$$

Where G_{sc}= Solar Constant (1367 W/m^2), n_d = day of the year, ϕ = Latitude, δ= declination angle, and ω_s= hour angle. The hour angle can be calculated by using equation 8.

$$\omega_s = \cos^{-1}\left(-\frac{\sin\phi\sin\delta}{\cos\phi\cos\delta}\right) \tag{8}$$

Where ϕ is the latitude and δ is the declination angle. Demonstrations and other equations used in this research can be found in solar energy references [10].

3. RESULTS AND DISCUSSION

3.1Solar Panels Efficiency

The open circuit measurements were performed using the circuit of the solar panels without the resistor. The GaAs solar panel open circuit voltage measurements are shown in Fig. 2a. The maximum open circuit voltage was found to be around 33.82 Volts for the maximum solar irradiance (1,227 W/m^2) measured during the experiment. Likewise, the Si panel's open circuit voltage relationship is shown in Fig. 2b. In this type of solar panel, the maximum voltage was found to be around 22.5 Volts for the highest solar irradiance in the experiment (1,227 W/m^2). The sun irradiance varied between 350-1227 W/m^2. The open circuit voltage relationship for the Si solar panel was not quite distinct and was assumed to be of second order with an R^2 of around 0.7167. For the GaAs unit, the R squared was found to be 0.9779 for a fourth-order relationship using a polynomial distribution.

The short circuit current (I_{sc}) measurements for the GaAs and Si solar panels are shown in Figs. 3a and 3b. The solar panels I_{sc} was obtained graphically from Figs. 3a and 3b, from the point with greatest current. The GaAs' I_{sc} was found to be 2.01 Amps, and the Si panel's I_{sc} was 2.44 Amps. These values will be the basis for the calculation of maximum power point (P_m).

Fig. 4 shows the calculated conversion efficiencies for the GaAs and Si solar panels on a typical sunny day in College Station, Texas. The average daily efficiency for the GaAs unit was found to be 18.36% compared with 14.02% for the Si solar panels or a difference of over 4%. Equation 1 was used for the calculation of maximum power for both systems. The plot of efficiencies as a function of solar irradiance variations is shown in Fig. 5. Note the decrease in the conversion efficiency as solar irradiance is increased. This can be a consequence of the increment in the surface temperature which increase with the increment in the solar irradiance, and the load effects [11]. The efficiency reduction related with an increment in the temperature has been reported by different authors showing reduction between 60-70% in Si solar panels [12]. The temperature effect in GaAs panels is lower than Si [13], which is an explanation for the best performance observed by GaAs panels. Data in Fig. 5 will be utilized to make a year-long inventory of the solar PV output using daily solar irradiance data for the experiment location. The trend line for each graph is also shown with very high degree of correlation. Thus, if solar irradiance is known each day for a given location, the yearly output of the solar PV cell may be easily estimated. Further, if the initial capital costs as well as operational costs are also known, the overall economic benefit of the unit may be evaluated appropriately. This is done by simply multiplying the solar irradiance received per unit area on a given day throughout the year with the solar collector area. If the unit is metered-in at the local utilities and the utilities cost is known ($/kWh), then the yearly revenue may be is estimated. These analyses will be presented in the next section.

3.2 Economic Evaluation of PV Systems Studied

To compare the economic return of the solar PV systems, it was necessary to simulate the solar panels' yearly performance from actual solar irradiance data available on a given location. Numerous cities worldwide have reported their solar energy potential and perhaps the basic data is the one similar to that shown in Fig. 6. This graphs shows the average solar energy received each month in units of MJ/m^2. This type of data was used to make a yearlong initial estimate of the performance of a solar PV panel when used in this location. The actual values of solar irradiance received are shown in Table 2. Included in Table 2 are the theoretical solar energy received each month (H_o) and the clearness index (K_t) in College Station, Texas. The clearness index is a factor that was used to calculate the actual solar irradiance received compared with the theoretical maximum possible solar irradiance received, if the sky were very clear and absolutely free of obstructions. K_t data was obtained from our laboratory data files in solar energy using the theoretical and actual radiation (actual solar irradiance received (H) = H_o x K_t). The solar panel units were facing directly south. The theoretical number of hours of sunshine is also needed in the calculations to convert a power output (kW) into energy (kWh).

Further assumptions include the use of about 15 units of the solar panel with an initial capital cost of $8,400 (Kyocera 2150 W system, multi crystalline Si) or an assumed 21 m^2 of a solar panel area. The unit will be net-metered in a utility that has a utility cost of approximately $0.12/kWh (or 12 cents per kWh). This will be compared with a similar GaAs solar PV panel with an assumed initial capital cost of $10,000. The bases for these costs are the following: $3/Wp for GaAs unit versus $2.04/Wp for the crystalline Si unit [14]. The total installed cost was assumed to be around triple the value for the crystalline Si or an assumed $4/Wp additional balance-of-system (BOS) cost for both systems [15]. BOS includes all additional cost to have the unit in full operation such as the batteries, converters, controllers, wiring and other switches. Thus, the overall cost used for the analysis was $7/Wp for GaAs and $6/Wp for the Si unit. On the average, a small farm with 40 cows will have a consumption of approximately 1,000 kWh/month of power and the assumptions were made to have this requirement supplied by the solar panels. This translates to a solar module with a rating of around 1,400 Wp which for the GaAs unit will have an initial installed cost of around $9,800 (assumed $10,000 above) and $8,400 for the crystalline Si.

The procedure for calculation is a simulation over a year using the product of K_t and H_o and the expected power output for a given day. This daily output is then added to provide a yearly estimate of the revenue over an assumed 20 year life of the units with no operating and maintenance cost. The revenue is simply spread out over the capital cost to determine the simple payback period (PBP). In this study, the yearly revenue for the Si system is around $1,120 versus $1,470 for the GaAs unit. One should do a much more complicated economic analysis depending upon the state and other fixed and variable cost data including use of tax rebate for the purpose. The calculations of this study showed that it would take about 7.5 years for the Si PV panels to recover the initial investment cost as against the net-metered revenue while 6.8 years for the GaAs unit, without any subsidy. Thus, there is a slight advantage for the GaAs PV units due to its higher conversion efficiency even though the initial capital cost is slightly higher.

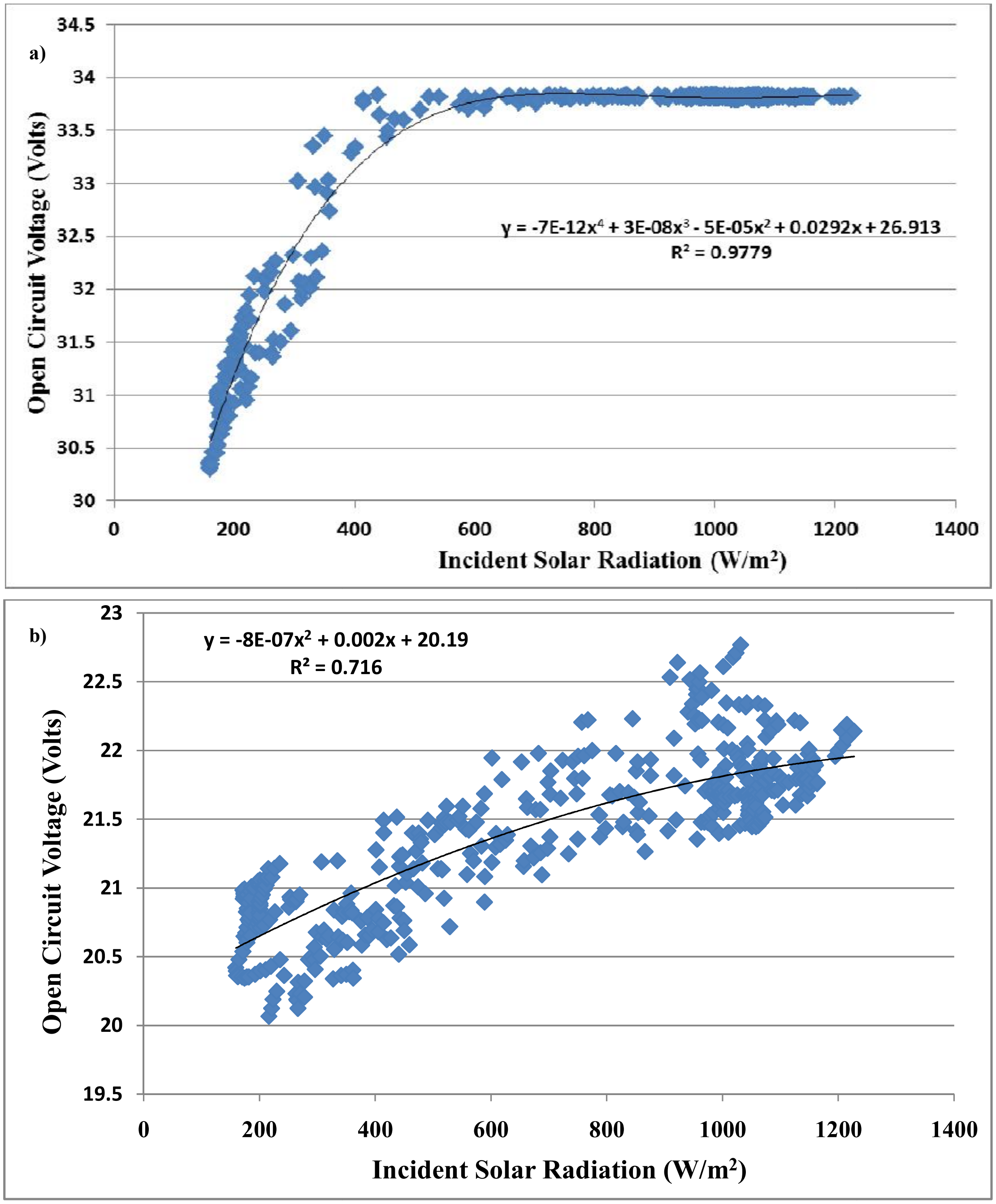
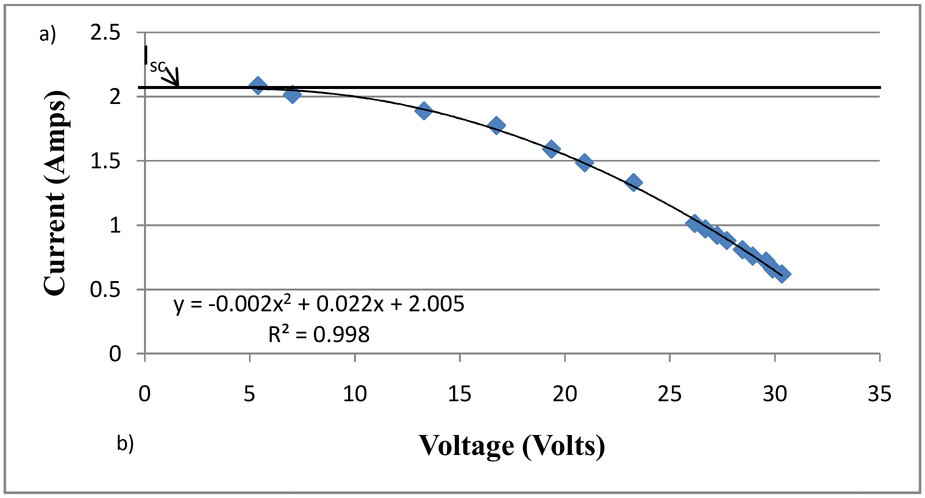


Fig. 2. Relationship between open circuit voltage and solar irradiance a) GaAs Solar Panel, b) Si Solar Panel



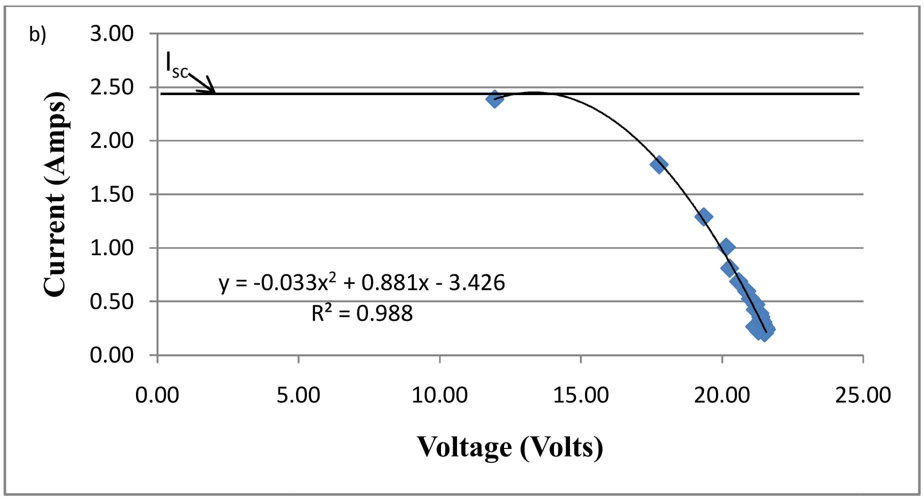


Fig. 3. Relationship between voltage and current, a) GaAs Solar Panel, b)Si Solar Panel

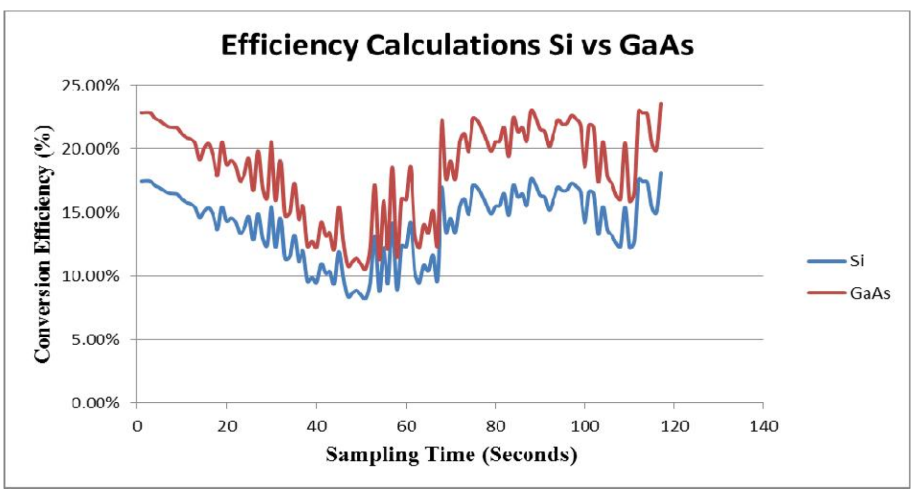


Fig. 4. Conversion Efficiencies for GaAs and Si Solar Panels

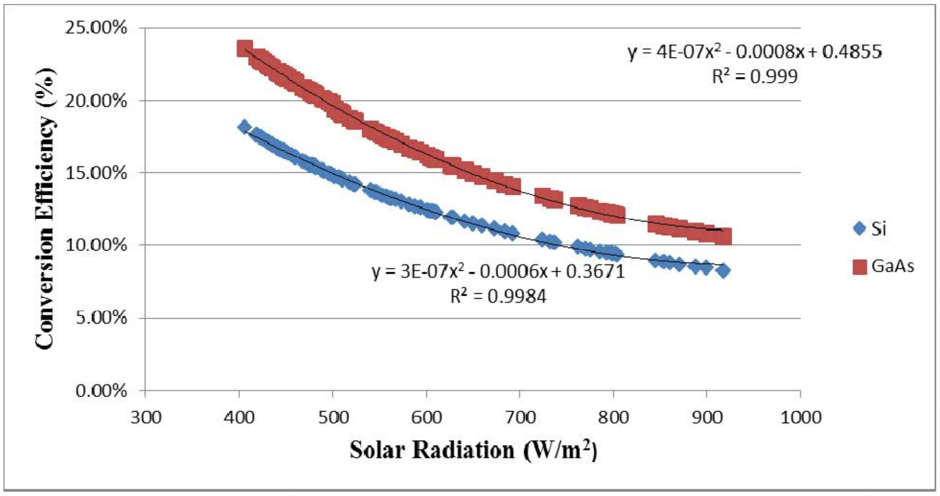


Fig. 5. Conversion Efficiencies for GaAs and Si Solar Panels as a function of solar irradiance

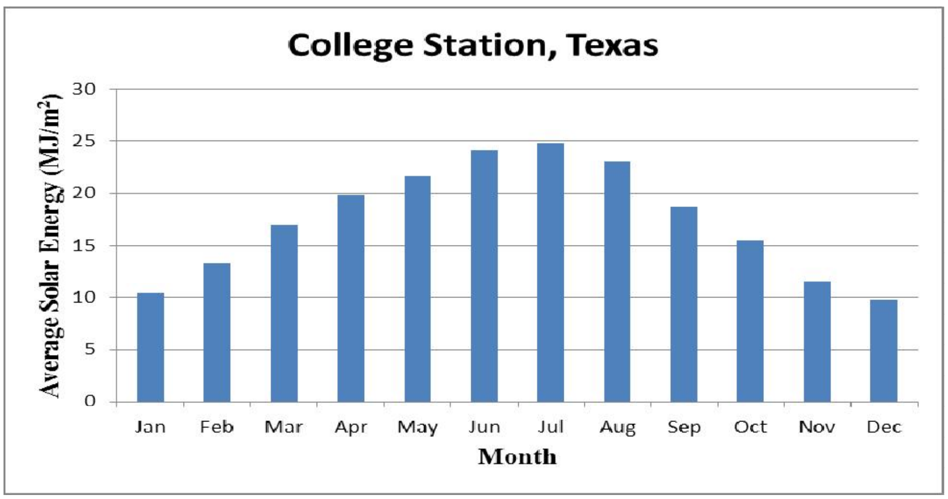


Fig. 6. Average Solar irradiance Received in College Station, Texas for a Year

Table 2. Solar irradiance Data in College Station, Texas

Month	H (MJ/m^2)	H_o (MJ/m^2)	K_t	Monthly revenue	
				Si	GaAs
January	10.4	20.91	0.498	63.68	83.39
February	13.3	25.86	0.519	72.60	95.08
March	16.9	31.56	0.536	95.86	125.53
April	19.8	36.74	0.537	108.44	142.01
May	21.6	39.97	0.539	121.90	159.63
June	24.1	41.18	0.585	121.23	158.76
July	24.8	40.56	0.613	122.97	161.03
August	23.0	38.10	0.609	114.56	150.02
September	18.7	33.77	0.566	96.77	126.73
October	15.5	28.07	0.573	81.82	107.15
November	11.5	22.53	0.523	64.05	83.87
December	9.7	19.67	0.497	59.29	77.65
Yearly Mean	17.4	31.58	0.550	93.60	122.57

The economics analysis will change if additional data are considered. What is shown in this study is a procedure for comparing solar PV units based on their actual field performance and the step-by-step procedure in comparing actual commercial PV units. This paper in no way recommends one type of solar PV system to another since the prices and individual state tax incentives will vary. For example, if there is a 50% subsidy on the total initial capital cost, the PBP will simply be reduced by half, making the system very attractive to farmers and ranchers, especially if the PBP can be reduced to less than 5 years (i.e. 3.4 years for the GaAs and 3.75 years for the Si system). The operating and maintenance costs for the solar PV system are very minimal and will not provide significant changes into the economic analysis over the life of the system. Perhaps, the most important maintenance cost for this system is the replacement of batteries. Deep cycle batteries are quite reliable and may not be replaced for at least 5 years. They are just quite expensive compared with automotive batteries. Thus, one would expect the purchase of new deep cycle batteries around every 5 years.

If the GaAs unit is to be operated on a concentrated mode (i.e. highly intense sunlight), the advantage may be more significant than with the multi-crystalline Si panels. The rebates and tax incentives will change the overall economics if they are included in the calculations. If for example the prices of the units are cut in half (say due to capital cost subsidy), then the payback period will be cut in half as well. The final application of the solar panels in a cattle farm will depend of the farmer necessity, this research showed the calculation for all the power requirements in a small farm, however the same calculation can be done to utilize solar energy independently in different application inside the farm such as water pumping, ventilation, electric fencing and building needs.

4. CONCLUSION

The technical and economical outline proposed in this paper was useful to decide between GaAs and Si panels using basic economic assumptions. In that way, it was calculated the conversion efficiency of the GaAs (18.36%) and Si (14.02%) panels under East Central Texas conditions. The economic study exhibited that Si panels has a recovery time (7.5 years) of the initial capital larger than the GaAs solar panels (6.8years). This paper did not recommend a specific solar panel over the other in every situation. In other locations will be necessary to correct the prices and individual state tax incentives. Future economic calculations should take into consideration government subsidies, rebates and tax credits to make the economic and technical analyses a more accurate tool to select solar panels.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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