
AC 2012-3376: UTPA SOLAR SYSTEM EFFICIENCY

Mr. Leonel Aguilera, University of Texas, Pan American

Leonel Aguilera earned his B.S degree in electrical engineering from the Technology Institute of Saltillo, Coahuila, Mexico in 2006. He is currently a M.S. in electrical engineering student at the University of Texas, Pan American, in Edinburg, Texas. He is an active researcher with interests in networking and renewable energy.

Dr. Jaime Ramos P.E., University of Texas, Pan American

Jaime Ramos, Assistant Professor, has been at The University of Texas Pan American since 2005, in the Department of Electrical Engineering. His research activities are directed towards the integration of renewable energy sources to the electric grid. He is the Principal Investigator for UTPA's three main solar facilities: the ENGR PV Fixed Array, the TXU Sun Tracking Arrays, and the Solar Observatory. Ramos is a licensed Professional Engineer in the state of Texas and Chair of the Rio Grande Valley Chapter of IEEE Power & Energy Society. Before coming to Texas, he accumulated significant experience in manufacturing, consulting, and teaching electrical engineering courses. He obtained a Ph.D. in electrical engineering in 1976 from Stanford University. Ramos has been an educator since 1977 of national and international universities including the University of Texas, Pan American, Edinburg, Texas; Universidad Autnoma de La Laguna, Mexico; Instituto Tecnologico de Estudios Superiores de Monterrey; and Instituto Politenico Nacional, Mexico.

Dr. Sanjeev Kumar, University of Texas, Pan American

Sanjeev Kumar, Associate Professor, is active in research, development, and teaching in the areas of computer network security, high-speed internet switching/routing, wireless ad hoc networks, computer architecture, digital logic systems, and smart grid. Before joining UTPA, Kumar worked with the leading networking companies in the United States. In the networking industry, Kumar played a leading role in planning, research, and development of new communications equipment and networks. Kumar has authored more than 50 technical papers. Kumar's research findings have been cited by other researchers in the field. Kumar has served as a member of technical program committee for international conferences and served on editorial board of several journals. He has been awarded U.S. and international patents for his inventions in the area of broadband networks. Kumar received the Ph.D. degree in computer engineering from North Carolina State University, Raleigh, N.C. He is the founder of NSF-funded Network Research Lab (NRL) in the Electrical/Computer Engineering Department. at UTPA, and an elected Senior Member of IEEE.

UTPA Solar System Efficiency

Abstract

Nowadays a lot of interest has been shown worldwide into Solar Energy Systems, since they represent revolutionary way to generate electrical power in a cleaner way, in order to help protect the environment.

Due to the capacity factor of Solar Photovoltaic, which is at most 30% we need to know how efficient our arrays are, and to ensure the efficiency is maximized in order to get a greater power production.

The research motivation of this paper is the development of a database system to store the gathered information from solar energy production, and to generate customized reports for the purpose of analyzing and comparing the amount of power within the two arrays that we have in campus, and to also study security aspect of data collection in future for smart grid project.

Our research objective is to measure the actual efficiencies of each one of our arrays in an accurate way.

The Solar System we have designed is the research methodology that gives the students access to a wide variety of data generated by the Solar Radiation Lab, ENGR and TXU arrays. They will have to calculate different angles of the sun at diverse hours of the day and the solar noon time in a manual way using formulas presented in this paper in order to compare their theoretical results with the actual measurements found in the system.

A compound of class exercises, homework and laboratory experiments have been designed to introduce this topic in a more enthusiastic, practical and visual way in order to enhance understanding about the great potential found in solar energy.

Introduction

We have observed through previous experience, that students are more interested about a specific topic when they get some hands on experience. This is with the purpose of proving that the theory they learned in the classroom has a wide range of application in the field.

As described in [5], the price of solar panels decreased 45% from 2008 to 2009, combined with an increase on their efficiency. Since photovoltaic systems become more popular, this fact reinforces the idea that students must be familiar with this kind of technology.

The way we are implementing this initiative, is through the development of a system that allows the students to access real time solar information, which is generated from the Photovoltaic devices located in the University of Texas-Pan American.

Once they obtain certain data, they can use the formulas presented in later sections of this paper to calculate the power expected from the Solar Arrays according to the amount of solar incidence throughout a specific period of time during the day. These results will help the students to calculate the efficiency of the Solar Cells.

Similar work has been shown on [6], where they access stored weather and solar information from databases to perform diverse calculations. On [7], Goswami emphasizes the environmental impact of using renewable energy, and the importance of Solar Education and student hands on experience and involvement, which is also mentioned on [8].

Solar System Description

We are able to gather solar energy from two Photovoltaic Arrays: The ENGR PV Array and TXU Array. The ENGR PV Array is a fixed array of 5 kW with a Collector Azimuth angle of 11° from the south, and a Tilt Angle of 10° . The TXU Array has a Solar Tracking System to increase the power efficiency production; it contains 2 solar trackers with 2 degrees of freedom each. Their rated maximum power is 2.75 kW, summing up a total of 5.50 kW [1].

The ENGR PV Array generates averaged measurements every five minutes, whereas the TXU Array is recording readings every fifteen minutes that are averaged every hour. This information is later used to populate our database records enabling the generation of customized reports, which include energy (kWh) and power (kW) measurements, and also the duration of the day. Both for a user selected period of time input containing start and finish date.

A Solar Radiation Lab was recently installed on the Engineering building rooftop; this device enables us to calculate the amount of power delivered by the sun throughout the day per square meter. The Solar Radiation Lab contains a Solar Tracker System able to collect measurements of direct normal irradiance (DNI), diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI); all of these measurements are in units of watts per square meter.

The database we have implemented is an online analytical processing (OLAP) Relational Database. The database was developed using MySQL, and a graphic user interface was created in C++, used in order to enable connectivity and query into the stored information. This database will also be used in future security research for smart grid project.

Illustrations of the ENGR PV Array, the TXU Sun Tracking Array, and the Solar Radiation Lab are shown in figures 1, 2, and 3 respectively.



Figure 1 - ENGR PV Array



Figure 2 - North Half of the TXU Sun Tracking Arrays



Figure 3 – This photo displays two pyranometers, one pyr heliometer, and the tracker.

Theoretical Calculations

In order to calculate the relative angles between solar position(β, ϕ), and PV Arrays(Σ, ϕ_p), we will assign the direction of south to the x axis, east to the y, and up to z.

The angles are defined as:

- β : Solar altitude or solar elevation.
- ϕ : Solar azimuth, south is zero degrees going positive to the east.
- Σ : Collector tilt angle.
- ϕ_p : Collector azimuth, zero when collector faces the equator.

As shown in figure 4.

From figure 5, the solar distance to the panel can be defined as:

$$\vec{r}_s = \hat{z}r_s \sin \beta + \hat{x}r_s \cos \beta \cos \phi + \hat{y}r_s \cos \beta \sin \phi \quad (1)$$

The unit vector in the direction to the sun is

$$\hat{r}_s = \hat{z} \sin \beta + \hat{x} \cos \beta \cos \phi + \hat{y} \cos \beta \sin \phi \quad (2)$$

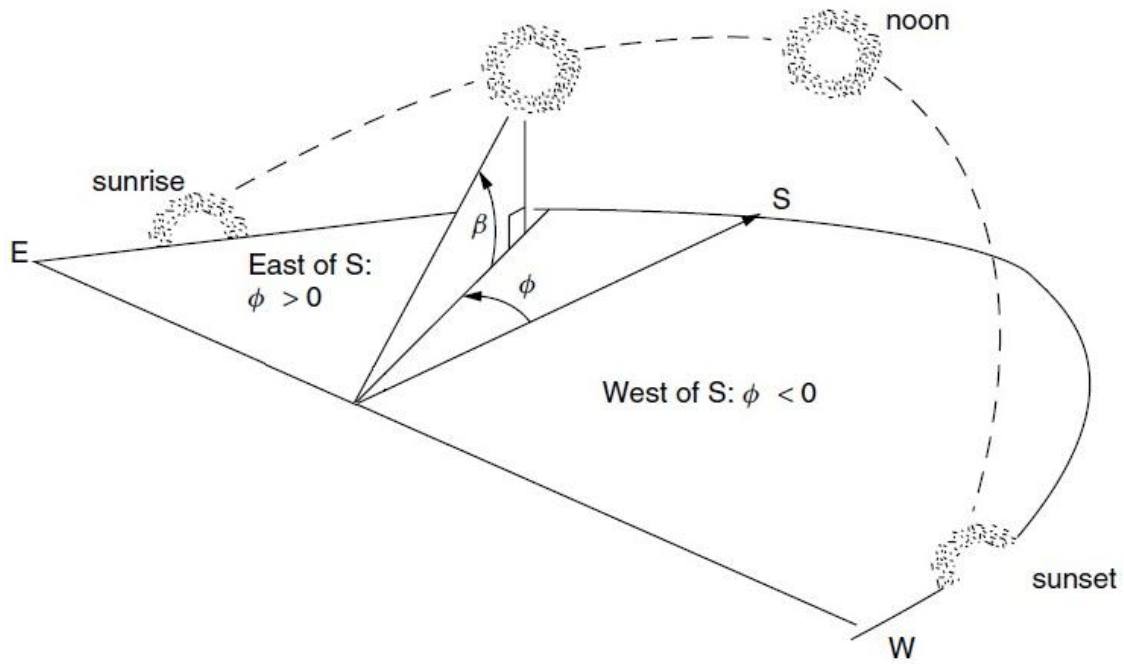


Figure 4 - Solar Position and Angles

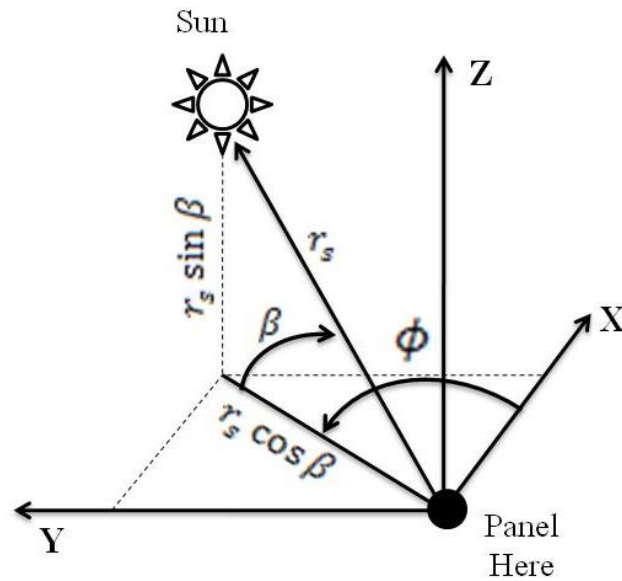


Figure 5 - Vector from the Panel to the Sun

The second important equation is the panel orientation (Σ : Collector tilt angle, and ϕ_p : Collector azimuth, if the panel is facing the equator, then $\phi_p = 0$). We must find an expression for the line perpendicular to the panel. This unit vector is denoted by $\hat{r}_p$.

Case a)

Panel lying horizontally, then

$$\hat{r}_p = \hat{z} \cos \Sigma \quad (3)$$

and $\Sigma = 0$.

Case b)

Panel standing vertically, and looking to the equator, $\Sigma = 90^\circ$; $\phi_p = 0$

$$\hat{r}_p = \hat{z} \cos \Sigma + \hat{x} \sin \Sigma \cos \phi_p \quad (4)$$

Case c)

Panel standing vertically ($\Sigma = 90^\circ$), and looking to the east ($\phi_p = 90^\circ$),

$$\hat{r}_p = \hat{y} \quad (5)$$

Therefore all three cases are satisfied by the equation:

$$\hat{r}_p = \hat{z} \cos \Sigma + \hat{x} \sin \Sigma \cos \phi_p + \hat{y} \sin \Sigma \sin \phi_p \quad (6)$$

The angle between a line normal to the panel and a line pointing to the sun is obtained with the dot product from (2) & (6)

$$\cos \theta = \hat{r}_s \cdot \hat{r}_p = \sin \beta \cos \Sigma + \cos \beta \cos \phi \sin \Sigma \cos \phi_p + \cos \beta \sin \phi \sin \Sigma \sin \phi_p \quad (7)$$

$$\cos \theta = \sin \beta \cos \Sigma + \cos \beta \sin \Sigma \cos(\phi - \phi_p) \quad (8)$$

Equation (8) is the desired result. The sun motion angles (β, ϕ) are determined by:

$$\sin \beta = \cos L \cos \delta \cos \phi + \sin L \sin \phi \quad (9)$$

$$\sin \phi = \cos \delta \frac{\sin H}{\cos \beta} \quad (10)$$

where:

L is the site latitude,

δ is the day declination,

H is the day hour ($H = 0$ for Solar Noon).

According to [2], the declination angle in degrees is:

$$\delta = (0.006918 - 0.399912 \cos \Gamma + 0.070257 \sin \Gamma - 0.006758 \cos 2\Gamma + 0.000907 \sin 2\Gamma - 0.002697 \cos 3\Gamma + 0.00148 \sin 3\Gamma) \left(\frac{180}{\pi} \right) \quad (11)$$

Which delivers a more precise result for the declination angles than those given in [3]:

$$\delta = 23.45 \sin \left[\frac{360}{365} (n - 81) \right] \quad (12)$$

Being n the day number of the year.

And the day angle is:

$$\Gamma = 2\pi \frac{(d_n - 1)}{365} \quad (13)$$

where d_n is the day number, starting at 1 for January 1st.

UTPA's Solar Radiation Lab

This instrument is capable of measuring the following solar irradiances in W/m².

- a) DN – Direct Normal, P_{DN}
- b) DH – Diffuse Horizontal, P_{DH}

The data acquisition system makes measurements every second; it performs 1-minute averages, writing the results in the database.

UTPA operates two solar arrays:

- a) A fixed ENGR PV Array, tilt angle of $\Sigma = 11^\circ$, and facing the equator $\phi_p = 10^\circ$
- b) A two axis TXU Solar Tracking Array.

Both arrays have 24 panels with capacity of 5.0kW and 5.5 kW as described previously.

Calculation of energy conversion efficiencies

The power intercepted by the ENGR PV array & the TXU Sun Tracking Array, must be calculated. These powers are [3, 4]:

$$P_{ENGR} = DN \cdot \cos \theta + DH \frac{1 + \cos \Sigma}{2} \quad (14)$$

$$P_{TXU} = DN \cdot 1 + DH \frac{1 + \cos \Sigma}{2} \quad (15)$$

ENGR PV Array

The most convenient way to operate this array for the calculation of its operating efficiency is at solar noon, and with its battery in a low state of charge. At solar noon $\phi = 0$ from equation (11); $\sin \beta = \cos(L - \delta)$, therefore $\beta = 90 - (L - \delta)$, and the incidence angle on the array from (8) if:

$\phi_p = 0$; Array facing the equator, then:

$$\cos \theta = \sin \beta \cos \Sigma + \cos \beta \sin \Sigma = \sin(\beta + \Sigma) \quad (16)$$

But $\beta = 90 - (L - \delta)$, so we obtain:

$$\cos \theta = \sin(90 - (L - \delta) + \Sigma) = \cos(L - \delta - \Sigma) \quad (17)$$

Therefore:

$$\theta = L - \delta - \Sigma \quad (18)$$

is a function of the declination.

TXU Sun Tracking Arrays

The solar power intercepted by these moving arrays is given by the equation (15); now Σ is a function of time. Equation (6) must be calculated from the figure 6:

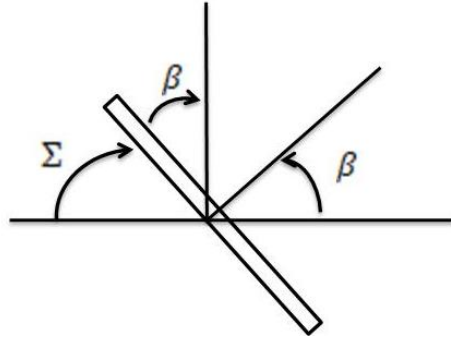


Figure 6 - TXU Sun Tracking Array, Panel Orientation

$$\Sigma + \beta = 90 \quad (19)$$

and also $\phi = \phi_p$, therefore $\cos \Sigma = \sin \beta$

$$P_{TXU} = DN \cdot 1 + DH \frac{1+\sin \beta}{2} \quad (20)$$

$$P_{TXU} = DN \cdot 1 + DH \left(\frac{1}{2} \right) (1 + \cos L \cos \delta \cos \phi + \sin L \sin \delta) \quad (21)$$

Again, if we perform the experiment of solar noon $\phi = 0$ then

$$P_{TXU} = DN \cdot 1 + DH \left(\frac{1}{2} \right) (1 + \cos(L - \delta)) \quad (22)$$

For these cases $\phi = 0$.

For experiments performed during any hour of the day then equation (14) & (15) must be calculated with a program which performs angle calculation every appropriate interval of time.

Example of efficiency calculation

We will calculate the efficiency of both Solar Arrays with measurements obtained on December 1st 2011; the Solar Noon was calculated to be at 12:22 PM.

The information gathered on that date and time is displayed on Table 1.

Table 1 - Measurements of Power and Incidence for Solar Noon on 12/1/2011

Array	Power (W)	Panels Area (m ²)	DH (W/m ²)	DN (W/m ²)
TXU	4776	35.04	105.6	760
ENGR	2870	39.12	105.6	760

Our site and array information is the following:

L – Latitude = 24.485°

δ - Declination = -21.691

Σ - Tilt Angle (ENGR PV Array) = 10°

ϕ_p - Azimuth Angle (ENGR PV Array) = 11°

We obtain the sun altitude angle:

$$\beta = 90 - (L - \delta) = 41.824 \quad (23)$$

For the ENGR Array, we use this value to obtain the incidence angle: Angle between sun's radial vector and collector's normal:

$$\cos \theta = \sin \beta \cos \Sigma + \cos \beta \sin \Sigma \cos \phi_p \quad (24)$$

$$\theta = 38.39$$

This value will be used on a modified version of (14) that includes the area, in order to obtain the power received in the array.

$$P_{ENGR} = \left(DN \cdot \cos \theta + DH \frac{1 + \cos \Sigma}{2} \right) \cdot A_{Engr} \quad (25)$$

$$P_{ENG} = 27,393.13$$

For the TXU Sun Tracking Array, we use a variation of (15), also including the area.

$$P_{TXU} = \left(DN \cdot 1 + DH \frac{1 + \cos \Sigma}{2} \right) \cdot A_{TXU} \quad (26)$$

$$P_{TXU} = 30,302.51$$

In table 2, we display a summary of the calculations that includes the efficiency of both arrays.

Table 2 - Efficiency calculation results

Array	Received Power (W)	Generated Power (W)	Efficiency (%)
TXU	30,302.51	4776	15.76
ENGR	27,393.13	2870	10.47

Student Evaluations and Technology Transfer

During summer of 2012, 2013, and 2014 using funds from a NSF RET Grant [10], Mounir Ben Ghalia and J. Ramos will train twelve high school science teachers in solar renewable energy and other fields of engineering. During these summer sessions the teachers will evaluate the laboratory experiments presented in this paper. We will also be able to evaluate areas in which further instruction is required, and use this information to adjust course syllabi when integrating the experiments. Students will complete evaluations for each experiment.

UTPA offers a course ELEE 4373 Renewable Energy, which is elective undergraduate course. These experiments would fit into the learning objectives for this lecture, considered to be taught to upper-level undergraduate students.

The database component will be used for Dr. Kumar's research on security evaluation for Smart Grid Project.

Conclusions

Through the experimentation done in our laboratory, we have been able to realize the impact on efficiency from a Solar Tracking Array, with respect of a fixed one. The students will be able to take advantage of the equipments deployed at the University of Texas-Pan American, and the experiments developed, in order to a better understanding of how the Solar Resource can be used to calculate a lot of different factors that influence the energy production of PV Arrays.

With implementation of database, it will enable data collection and newer security research for Smart Grid in near future.

With the implementation of the Solar Radiation Lab, they are able to get measurements of the received power from the sun, and to use them as a tool in the learning process, which we think, will be greatly improved by the hands on experience on these facilities, and will also prepare them to be aware of the technology deployment in the actual world, which is evolving in a faster and revolutionary way.

Acknowledgement

This material is based upon work supported by the Department of Energy under award number DE-EE0004007.

References

- [1] Jaime Ramos et al, "Commissioning a 5 kW PV array for Electrical Engineering University curriculum", 2011 ASEE General Conference paper 256, Vancouver CA.
- [2] Muhammad Iqbal, "An introduction to solar radiation", Academic Press 1983.

- [3] Gilbert M. Masters, “Renewable and efficient electric power systems”, 2004 John Wiley & Sons.
- [4] T. Stoffel, et al, “Concentrating Solar Power. Best practices handbook for the collection & use of solar resource data”. Technical report NREL/TP-550-47465, Sept 2010.
- [5] James M. Bing. “Advances in Commercial Applications of Photovoltaic Technology in North America: 2009 Update”. IEEE Power & Energy Society. July 2010
- [6] Manuel Blanco, et al, “Wireless solar radiation and meteorological instrument for K-12 Technology Education”. ASEE Annual Conference 2003.
- [7] D. Yogi Goswami, “Present Status of Solar Energy Education”. ASEE Annual Conference 2001.
- [8] Arthur Haman, et al, “A student-centered solar photovoltaic installation project”. ASEE 2007.
- [9] UTPA Solar Radiation Lab link - http://www.nrel.gov/midc/utpa_srl/
- [10] NSF RET Grant: Research Experience for Teachers in emerging and Novel Engineering Technologies in the Rio Grande Valley. NSF Award CNS – 1132609.