A Renewable Energy Undergraduate Course Underlining the Analysis of Collected Solar Radiation

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I am a Senior at University of Texas Rio Grande Valley who is working to obtain his Bachelors Degree in Science in Electrical Engineering. I have interests in renewable energy, and hope that through important research, I can help impact the world with a more efficient, more environment friendly, and more innovative energy source on which we can fully depend.

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Dr. Hiram Moya earned his Bachelor of Science degree in Industrial Engineering from Texas A&M University at College Station, Texas in 1996. After working in Accenture for 5 years, he founded and became the managing Partner of HMGroup LLP. While working in his firm, Dr. Moya was also taking graduate courses from the University of Texas at Dallas, and online courses from Texas A&M University. In December 2004, he earned his Master of Science degree in Engineering Systems Management. Later, he returned as a full time student and completed his Doctor of Philosophy in Industrial and Systems Engineering in 2012.

Dr. Moya's academic experience includes a year serving as Visiting Assisting Professor at Texas A&M University, and in 2013 he has joined the Manufacturing Engineering department at The University of Texas–Pan American. In the fall of 2015, UT–Pan American, UT Brownsville, and the Health Science Center became University of Texas Rio Grande Valley, and the department's name is now the Department of Manufacturing and Industrial Engineering. Dr. Moya's research interests include Queueing Theory, Optimization, Simulation, Applied Probability, Quality, and Supply Chain Management. Some of the areas applied in the research include, Homeland Security, Healthcare delivery, web-based decision support tools, systems engineering in healthcare and process improvements. Dr. Moya has been successful in obtaining research funding from DHS to complete border security research projects.

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1- INTRODUCTION

The growth of generating electricity through solar radiation has increased steadily over the last ten years [1]. At the same time, the cost of solar electricity has decreased steadily [2]. In the 2016 State of the Union address, President Obama mentioned that “on rooftops from Arizona to New York, solar is saving Americans tens of millions of dollars a year on their energy bills, and employs more Americans than coal -- in jobs that pay better than average” [3]. These trends support an optimistic view of the future of the solar industry for the years to come.

The first step to an engineering design of a solar facility is to obtain information regarding the solar radiation available at the site of installation under study. Several sources of information are available, such as NREL’s PVWatts Calculator, NREL’s solar maps, and NREL’s Measurement and Instrumentation Data Center.

The first data requirement is the solar energy density, expressed in kWh/m^2, and collected over some time period, from a month to a year. This information plus the cost of electricity, and the cost of the solar installation are necessary for the engineering design of a solar facility.

From NREL’s MIDC database, the solar irradiations, in $Watts/m^2$, can be obtained minute by minute, for every day of the year. The data is more complete, and allows the analysis of the solar resource, which determines variability, clearness, and energy density.

2- RELEVANCE OF DESCRIBED EFFORTS

The focus of the Renewable Energy course imparted at this University is solar energy. In this course the authors wished to remark the importance of evaluating the local solar resource. Towards this end, a string of seven learning activities were developed, starting with three preparatory exercises. The learning objectives of the following four exercises are to train the students to use the data of NREL’s Measurement and Instrumentation Data Center

The UTRGV campus has considerable infrastructure to conduct enhanced learning and research in the fields of solar energy assessment and photovoltaic electricity generation. Furthermore, some of these experiences can be emulated by other engineering schools at low cost.

3- USE of PEDAGOGICAL THEORY

The authors believe in the model of hands-on laboratories and computer simulation as the best suited method to attain the educational objectives and outcomes.
Traditional pedagogical methods in engineering often favor lecture based teaching but the authors believe in the model of hands-on laboratories and computer simulation as the best suited method to attain the educational objectives and outcomes. This thinking and practice is supported by research that has focused on a hands-on, active learning approach to teaching engineering concepts [4, 5]. Active learning has long been believed to be an ideal form of instruction compared to a more passive approach to teaching particularly in fields such as education and the humanities but in science, technology, engineering and mathematics (STEM) related fields, lecture based instruction remains the predominant form of instruction. Recent research on active learning in STEM fields perhaps presents a shift in pedagogy (Freeman, et. al. 2014). Building on this work, the authors have identified active learning as the preferred form of instruction, in undertaking their research.

4- EDUCATIONAL OBJECTIVES and OUTCOMES

The following general and specific student outcomes come from UTRGV's Electrical Engineering Department.

General Educational Outcomes- it will be demonstrated that the student:

1- is able to use knowledge of mathematics, basic sciences and engineering to analyze (identify, formulate and solve) problems in electrical engineering
5- is able to communicate ideas effectively in graphical, oral and in written media.

Specific Educational Objectives- students graduating from the *EE* program should demonstrate:

1- (D)- an ability to create and use software both as an analysis and design tool, and as part of systems containing hardware and software
2- (d3)- familiarity with at least one high level programming language, one assembly language, and one mathematical software package.

To support the desired student outcomes, the following activities were developed for the course and to be completed by each student:

1- Activity at the sundial.
2- Clear sky insolation calculations.
3- Determination of solar array efficiency.
4- Downloading and reading data from NREL's MIDC Center.
5- Processing daily insolation data.

6- Analyzing daily insolation data.
7- Final Project

Activity	Learning Objectives- to learn	Outcomes- to know or do
1- Exercises at XXX Sundial, during two days, months apart. At solar noon measure the length of the shadow cast by sundial column	1- Study the sun motion: altitude and azimuth angles 2- Calculate day's declination angle. Observe its variation during the year	1- Calculate the Air mass 2- Determine the height of the sundial column. 3- Understand the difference between clock time and solar time
2- Clear Sky Insolation Calculator	1- Distinguish the different paths followed by radiation when reaching a solar panel 2- Assess the effect of the panel's tilt angle and orientation	1- Compute and compare the three types of radiation 3- Practice writing Excel programs to solve engineering problems
3- Solar Panels Efficiency	1- Use array's electricity power and energy production 2- Install simple global irradiance sensor in the plane of the array	1- Use sensor data to calculate the sun power intercepted by the array 2- Time match received solar power and electricity power delivery 3- Determine the efficiency of the array. 4- Assess the power gain of the array by cleaning the panels
4- Downloading and reading irradiance data from NREL/MIDC	1- Access NREL/MIDC website 2- Explore selected Solar stations data. 3- Correlate time zones and standard longitudes	1- Inspect radiometer characteristics for Global Horizontal and Direct Normal irradiance 2- Download GHI and DNI daily data
5- Processing daily GH insolation data	1- Use MATLab program to analyze minute-by-minute solar data 2- Observe the variable character of solar radiation. 3- Observe the difference between clear sky model and measured irradiances	1- Distinguish the effect of clouds and solar motion over the variable solar output 2- Compute clearness and variability indices 3- Classify solar days according to its clear and variable characteristics
6-Analyzing daily DN insolation data	1- Observe the different shapes of GH and DN irradiance 1-min data	1- Compute the daily insolation yields

	2- Learn the significance of the clearness and variability indexes as shown by their scatter plot 3- Use MATLab to analyze daily insolation [kWh] produced by GHI and DNI	2- Analyze peak DN irradiance as delivered by measurement and calculation 3- Classify solar days according to its clear and variable characteristics
7- Collective exercise: analyze irradiance data from 12 selected NREL/MIDC labs	1- Display daily data during one month 2- Compare sites using solar parameters	1- Classify site according to clear and variable indices 2- Classify sites according to insolation during the month

Table 1- List of participant Activities with specific learning objectives and outcomes.

Activity # 1: Basics of Solar Trajectory in the Sky.

Participants meet at the Sundial during different months of the semester, at noon time, and perform simple measurements:

Activity # 2: Clear sky insolation calculator.

Following [6], participants created a calculator for direct, diffuse and reflected radiation, using a spreadsheet. The exercise was done for different locations, hour of day, and panel's tilt and orientation.

Activity # 3: Determination of Solar Panels Efficiency.

Endowed with an inexpensive pyranometer, participants measured the global irradiance in the plane of the array of a campus photovoltaic array. Given the solar array's power generated at the time of the measurement, the efficiency of energy conversion was determined. The impairing influence of dirt over the panel's surface was assessed.

Activity # 4- Download and read data from NREL's MIDC Center.

Twelve solar stations grouped by MIDC [7] were selected and assigned to 23 students for analysis. These stations are distributed in 5 time zones within USA and are equipped with different types of radiometers. Table 2 identify these stations. Participants downloaded daily data for the full month indicated in the Table, in the format of csv files. There are two types of files according to the radiometer type (DN or GH), and the csv files contains 961 rows, for each minute from 4 AM to 8 PM. A valuable outcome of this exercise is to explore the wealth of data available in the web for the assessment of solar resources, such as MIDC and PVWatts, and to classify the supply of radiometers and techniques available for the measurement of solar irradiance

					Radiometer type		
	-		Time Zone	Dates	DNI	GHI	

Team	Solar Radiation Observatory	Acronym	GMT	2015			Ref
1	NREL Solar Radiation Research Lab (BMS)	NREL-BMS	-7	4-1, 4-30	CHP1	CMP11	[8]
2	NREL Vehicle Testing and Integration Facility RSR	NREL-RSR	-7	4-1, 4-30	Calculated	RSR	[9]
3	Solar Technology Acceleration Center (SolarTAC)	NREL-TAC	-7	3-1, 3-31	CH1	CMP22	[10]
4	SOLRMAP University of Arizona (OASIS)	UA-OASIS	-8	4-1, 4-30	CHP1	CMP22	[11]
5	SOLRMAP Loyola Marymount University (RSR)	SOLRMAP-LOY	-8	3-1, 3-31	Calculated	RSR	[12]
6	SOLRMAP Sun Spot Two - Swink (RSR)	SOLRMAP-SWINK	-7	1-1, 1-31	Calculated	RSR	
7	Nevada Power Clark Station	NEV-CLARK	-8	2-1, 2-28	no data	CMP3	[13]
8	University of Nevada - Las Vegas	UNEV-LV	-8	3-1, 3-31	NIP	CM3	[14]
9	Oak Ridge National Laboratory (RSR)	ORNL	-5	3-1, 3-31	Calculated	RSR	[15]
10	Natural Energy Laboratory of Hawaii Authority (NELHA)	NELHA	-10	3-1, 3-31	N/A	CMP11	[16]
11	Sacramento Municipal Utility District (Anatolia)	SMUD	-8	4-1, 4-30	Calculated	RSR	[17]
12	University of Texas Pan American	UTPA	-6	3-1, 3-31	CHP1	CMP11	[18]

Table 2- NREL-MIDC solar stations relevant characteristics for this course.

Activity # 5: Processing daily Global Horizontal Irradiance data.

At this stage of the course each group of participants have 30 or 31 csv files, each one containing 961 rows (minute by minute) of data of Global Horizontal irradiance, as well as a similar set of Direct Normal irradiance.

DATE	CST	Global Horizontal [W/m^2]
8/22/2015	4:00	-2.54176
8/22/2015	4:01	-2.54742
…	…	…
8/22/2015	7:35	162.14
8/22/2015	7:36	155.087
….	…	….

8/22/2015	19:59	-2.71523
8/22/2015	20:00	-2.71525

Table 3- Contents of 20150822GH.csv file

Files can be named as *yyyymmddGH.csv* and *yyyymmddDN.csv*. Participants employed a domestic MatLab program to read and make a daily plot of the irradiance csv files, in units of [Watts/ m²], downloaded from the assigned solar stations. See Figure 1 for an example of a measured and calculated GH Irradiance from a MIDC Solar station. This way, students learned about the variable characteristics of solar radiation, distinguished the effects of clear and overcast days, and observed the positions of dawn and dusk in the graph.

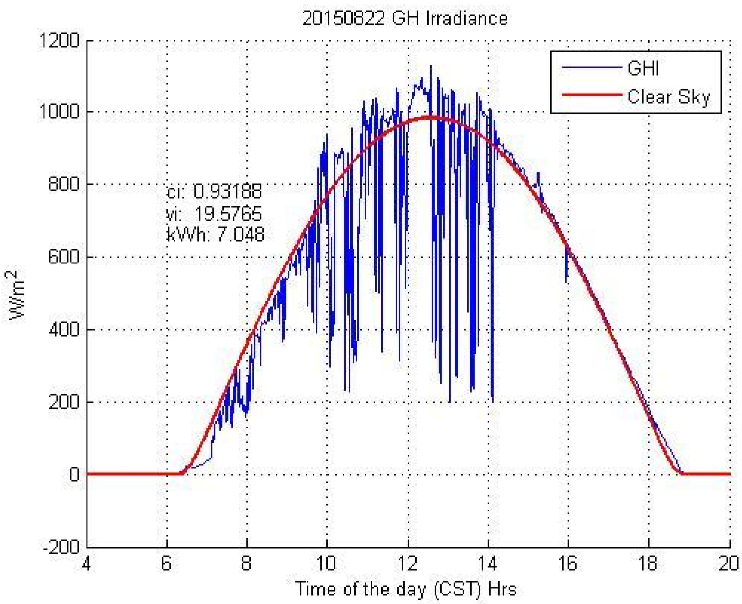

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Figure 1- Example of a measured and calculated GH Irradiance from a MIDC Solar station.

The MATLab program calculated the day insolation, in Units of kWh/m², by adding the 961 irradiances, and multiplied them by 1/60×1/1000. The program also calculated, and plotted over the previous graph, the minute-by-minute irradiance calculated using a model of a clear sky atmosphere, as described by Masters [6]. Any discrepancies between the sunrise points of both graphs will indicate an offset time zone and local longitudes. The product of this Activity is 30 (31) graphs, which were labelled *yyyymmddGH.jpg*.

Activity # 6: Processing daily Direct Normal Irradiance data.

This activity is follows a procedure similar to activity # 5, but applied to direct normal irradiance csv files. The outcomes of this activity allow the students to identify the particular shape of the DN irradiance graphs when compared to the GH irradiance graph. As the MATLab program calculates the daily irradiance [kWh/m²] for activities # 5, # 6, participants learn to assess the differences of direct, global and diffuse radiation at the particular station. Figure 2 displays such a case for a clear day.

The relation among the three irradiances is given by the following equation,

$$GHI = DNI \cos(szA) + DHI \qquad (1)$$

Where *szA* is the zenith angle.

Activity # 7- Collective Exercise. Comparing Sites with respect to their solar parameters- Two sites are compared according to three parameters: clearness index, variability index and daily insolation. The sites are at the University of Arizona SOLRMAP station, and The University of Texas Pan American station. The results are shown in Figures 3 and 4. In Figure 3, OASIS April days are *Clear*, whereas UTPA days are *Variable*. In the second figure the average daily insolation of OASIS is larger than UTPA's by 2.25 kWh/m^2 .

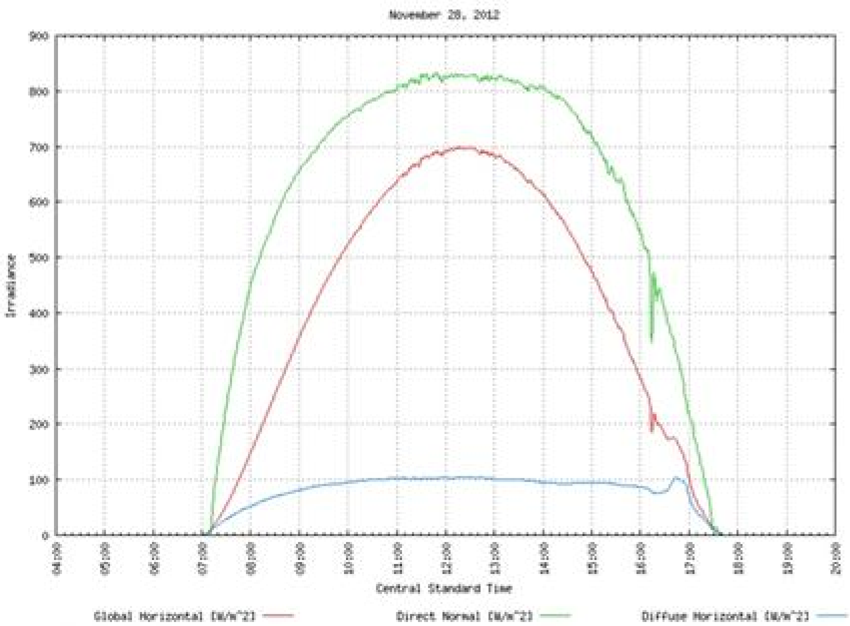

Figure 2- Displays three irradiances, Global Horizontal, Direct Normal and Diffuse Horizontal

5- CLASSIFYNG SOLAR DAYS-

Global Horizontal Irradiance. Table 1 includes two important learning outcomes for the classification of solar days according to its clarity and variability. The Clearness Index is a measure of how clear is the sky during a given period; when the solar resource is available to its full at the ground level the Clearness Index would ideally have a value $CI = 1$. It is also possible that $CI > 1.0$, during those periods when the presence of clouds act as concentrators of solar rays. On the other hand, when clouds may be casting shadow over the area of interest, the solar resource for photovoltaic power generation is poor, and *CI* would be low. If the sun light is fully blocked, then *CI* = 0.

To obtain the Clearness and Variability Indexes, two pieces of information are needed:

1. The set of measurements of the local Global Horizontal Irradiance GHI_{MEAS}[k], which can be downloaded from NREL's Measurement and Instrumentation Data Center [7], for later use. The instrument takes measurements every second, writes 1-minutes averages into the database. The time stamp is Standard Central Time. It is also possible to download selected hourly data from MIDC
2. A calculated time-series Clear sky Global Horizontal Irradiance $GHI_{CLEAR\text{-}SKY}$[k], in synchronism with the measured GHI_{MEAS}[k] time series. The former is calculated in solar time; the latter are obtained in standard time. Reference [19] offers a variety of methods to calculate the clear-sky irradiance. We have chosen one due to B. Harwitz, due to its simplicity.

$$CI = \frac{\sum_k GHI_{MEAS}[k]\Delta t}{\sum_k GHI_{CLEAR-SKY}[k]\Delta t} \tag{2}$$

Given *CI*, Equation (1) allows the calculation of the energy, in W-h, collected by the instrument during one day. The index k runs over the number of time intervals (minutes) = 960 from 4 AM to 8 PM, in the day.

This variability index is a measure of the variability of solar radiation, which is primarily caused by two factors: the motion of the sun in the sky, and the presence of clouds, which are also moving and changing, during the day. Solar Resource Variability is explained in References [6, 20]. Variability accounts for the "noise" of the solar radiation graphs, shown in Figure 1. This phenomenon is worrisome to (electric power) system operators. A stand-alone solar farm can be knocked out quickly without advanced notice.

In Reference [20] several criteria for detecting clear sky periods are discussed. The criterion selected to be used here measures variability by calculating the vertical displacement between adjacent points of the *GHI* time series:

$$Displacement = \sum_k \sqrt[2]{(GHI_{MEAS}[k] - GHI_{MEAS}[k-1])^2}$$

Here, the strength of the spikes are large contributors, while smooth variations are low contributors. The *VI* formula is

$$VI = \frac{\sum_k \sqrt[2]{(GHI_{MEAS}[k] - GHI_{MEAS}[k-1])^2}}{\sum_k \sqrt[2]{(GHI_{CLEAR-SKY}[k] - GHI_{CLEAR-SKY}[k-1])^2}} \tag{3}$$

In (2) the units for *VI* are null.

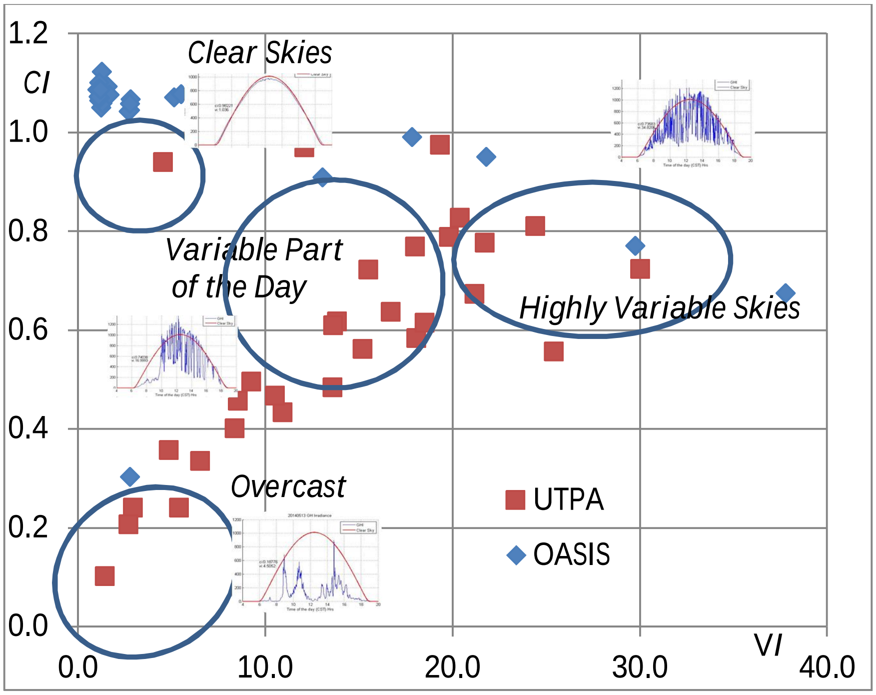

Figure 3- GHI Daily Clearness and Variability Indexes at OASIS and UTRGV, April 2015.

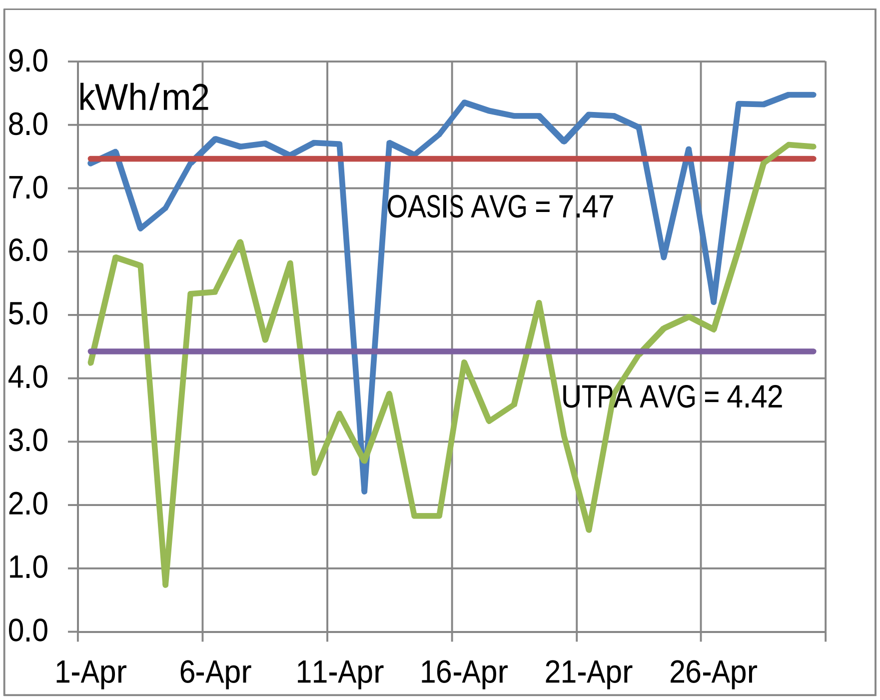

Figure 4 – April 2015 GH Insolation at OASIS and UTRGV.

6- ASSESSMENT

During the course of ELEE 4373 Renewable Energy questionnaires were handed out to determine whether participants had increases their levels of knowledge, interest and confidence in learning engineering.

The following questions were posed in all Activities. Their responses are summarized in Table 4.

1- Was the purpose of this activity clear?
2- Were the objectives met?
3- Will this activity benefit me?
4- Were the contents included in the activity related to the objectives?
5- The activity has increased my interest in Solar Energy.

Question 1- Was the purpose of the activity clear?			
Activity = 1	N = 15	Mean = 1.53	Std dev = 0.14
2	10	1.30	0.16
3	17	1.12	0.17
4	21	1.33	0.11
5	19	1.16	0.12
6	18	1.44	0.15
7	22	1.59	0.11
Question 2- Were the objectives met?			
Activity = 1	N = 15	Mean = 1.53	Std dev = 0.14
2	10	1.10	0.19
3	17	1.24	0.11
4	21	1.33	0.13
5	19	1.26	0.13
6	18	1.22	0.20
7	22	1.45	0.11
Question 3- Will this activity benefit me?			
Activity = 1	N = 15	Mean = 1.53	Std dev = 0.14
2	9	1.22	0.16
3	17	1.18	0.16
4	21	1.19	0.15
5	19	1.21	0.13
6	18	1.39	0.12
7	22	1.41	0.11
Question 4- The contents of this activity were related to the objectives			
Activity = 1	N = 15	Mean = 1.53	Std dev = 0.14
2	10	1.40	0.17
3	17	1.29	0.12

4	21	1.29	0.13
5	19	1.45	0.12
6	18	1.33	0.12
7	22	1.59	0.13
Question 5- This activity has increased my interest in solar energy			
Activity = 1	N = 15	Mean = 1.53	Std dev = 0.14
2	10	0.90	0.29
3	17	0.94	0.19
4	21	1.10	0.17
5	19	1.11	0.16
6	18	0.94	0.23
7	22	1.41	0.11

Table 4- Students' response to selected questions

Participants were able to write their response using a normal Likert scale, from *Strongly Agree* = 2, to *Strongly Disagree* = –2, with *Neither Agree nor Disagree* receiving a value of zero.

The questionnaires also included questions regarding the activity. Notice from Figure 5, that the resulting mean for most questions has a value greater than 1, resulting from an answer of *Agree* or *Strongly Agree*.

Activity	Question	N	Mean	Std. dev.
1	I can now tell the difference between solar and clock time	15	1.40	0.14
1	I can now explain to anybody the significance of the declination angle	15	1.13	0.14
2	I can now tell the importance of the collector tilt and orientation	10	1.20	0.14
2	I will use this Calculator for the analysis of solar solutions	10	1.20	0.21
3	I am aware of how the solar power generation data was obtained	17	1.06	0.14
3	I am aware of the instrument to measure Irradiance [Watts/m^2]	17	0.94	0.14
3	I can now explain how to determine and calculate the efficiency of solar panels	17	1.00	0.09
4	I learned about the instruments in use to measure solar irradiation	21	1.24	0.17
4	I was able to make a record of the site's coordinates and local time meridian	21	1.38	0.11
4	I was able to download easily and quickly daily 1-minute records of GHI and DNI.	21	1.29	0.13
5	Solar days can be classified by the use of clear and variability indexes	19	1.26	0.13

5	This activity helped to understand what is a clear day and what is a variable day	19	1.05	0.18
5	The daily insolation in *kWh* is a good metric to classify solar sites	19	1.16	0.14
6	I understand why DN plots have a shape which is wider that GH plots	19	0.95	0.18
6	Comparing DN and GH sets a base for recommending the use of concentrator or flat collector technology.	18	1.00	0.24
6	The air mass travelled by sunrays determine the shape of the irradiance plots	18	0.94	0.23
7	Increased my understanding of the methods in use to collect solar energy	22	1.55	0.11
7	Increased my understanding to classify sites according to their solar energy input	22	1.55	0.11

Table 5- Student's data used to evaluate achievement of learning outcomes.

Two open questions were also posed to them:

1- What I liked most about this activity was. Following Table lists their responses by activity

Activity	Selected responses to: What I liked most about this activity was
1	We learned how to use the solar system to our advantage. It was a great activity. Understanding how the sun has a different trajectory path through the year
2	The ease with which the Excel program could determine insolation if the program was coded correctly. Finding that we can use this for real life situations.
3	The simplicity behind the calculation of the data, and how well the idea behind the HW was presented. Being able to process real data and interpret the results
4	Review of all the data from different research labs across the nation. See the discrepancies between sunny and cloudy days
5	How we interpret the data using MatLab. It show us actual data of an actual solar station. Very informative. Everything
6	That we get to see the plots. The difference in data of DN and GH. Experience working with data (2)

7	Understanding concepts and how to interpret data to make proper judgements for placing solar farms. Using live data and presenting my final project report. Learning how renewable energy is actually harnessed and how to most efficiently and effectively analyze data to make engineering decisions Presenting my final project report

Table 6- What I liked most about the course responses

2- What I disliked more about this activity was: Following Table lists their responses by activity

Activity	Selected responses to: What I disliked most about this activity was
1	That I didn't know this before. Going to the sundial at a specific time. Many cloudy days didn't allow us to perform the activity (7)
2	Equations get messy. I'm not really skilled at Excel. Didn't know how to use the local time converter
3	The efficiency calculation was a little unclear. More information on LICOR radiometer and solar array power generation. It was a little difficult to understand at first
4	Too much data. The much time taken to download and rename the files. For one month you have to download 30 GH files and 30 DN files
5	The amount of tedious work to do to get the files working (2). Nothing (3). Very time consuming
6	Too much time fixing Excel spreadsheets. I prefer to spend more time learning about the topic with problems from book or other problems. Nothing (3)
7	The collection of data took much time when making conclusions from solar. Not being able to physically go to data site. Nothing (3)

Table 7- What I disliked most about the course responses

At the end of the course students evaluated the instructor using the standard tool of the university. Their responses are listed in the following Table

Question	N	Mean	Std. dev.
The instructor clearly defined and explained the course objectives and expectations	16	1.44	0.16
The instructor was prepared to teach for each instructional activity.	16	1.25	0.20
The instructor communicated information effectively.	16	1.38	0.19

The instructor encouraged me to take an active role in my own learning.	16	1.38	0.16
The instructor was available either electronically or in person.	16	1.56	0.16

Table 8- End of course student evaluation

7- CONCLUSIONS

The students' responses indicate the most had a positive experience from the class environment using hands-on activities to learn about renewable energy and how to use engineering in designing a solar facility. The class is exposing students to renewable energy, and the analysis of collected solar radiation.

In § 4 of this paper, Educational Objectives and Outcomes, two general educational outcomes and two specific educational objectives were outlined. After taking this course, the authors assert that students complied with them.

All activities in Table 5 were designed with a relevant content of math, basic science, and engineering to solve problems in renewable energy field. Table 6 shows that students did write Excel and Matlab code for completing the analysis called for in activities # 2, 4, 5, 6, and 7. Furthermore, for activities # 5, 6, and 7, students practiced the communication of ideas effectively in graphical, oral and written media, as also seen in Table 6.

Finally, Tables 1 and 8 include evaluations of student satisfaction. Their responses have been positive, and the authors feel encouraged to continue to use and enhance these methods

8- SELECTED LIST of ACRONYMS

CH1, CHP1- Pyrheliometers

CM3, CMP11, CMP22- Pyranometers

DHI- Diffuse Horizontal Irradiance [Watts/m^2]

GHI - The Global Horizontal Irradiance [Watts/m^2]

DNI - Direct Normal Irradiance [Watts/m^2]

G-POA-I: Global Plane of Array Irradiance

CI – Clearness Index

VI – Variability Index

NREL: National Renewable Energy Laboratory

MIDC: Measurement and Instrumentation Data Center

NIP- Normal Incidence Pyrheliometer

POA: Plane of Array

RSR- Rotating Shadow Radiometer

Δt - Time Interval

SC: Solar Constant = 1,367 Watts/m^2

szA- Sun Zenith Angle

UTRGV- University of Texas Rio Grande Valley

μ - mean

σ – standard deviation (N-1)

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