

Implementation of algorithmic techniques to facilitate design of solar power systems for Mauritius

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Abstract. The toolbox developed at Sandia National Laboratory (SNL), incorporates a range of well documented mathematical models, which provide scientific insight in to a number of aspects involved in the design of solar power systems. Of first and foremost importance is the need to acquire the capability to generate pre-processor input for the toolbox. As part of this strategy, the Solar Position Algorithm (SPA), developed at the American National Renewable Energy Laboratory (NREL), has been ported to evaluate parameters like zenith and azimuth angles for several geographical locations of Mauritius. Computations were carried out for two different seasons and for two locations, one at the University and the other at the 15 MW National Solar Power Plant, Bambous, Mauritius. The enormity of the task can be understood by realizing that we need both the solar position and weather data for several locations that would also vary with time and date. The importance of capturing such information on a high-resolution space (in order to generate Mauritius Energy Resource Map) is outlined in great detail. Experiments were carried out using solar module analyzer and the results obtained helped us to understand the pattern of variation of design parameters. This information is necessary for validation of the theoretical models. Sandia has implemented the package both in Python and MATLAB. To understand the fundamentals better, for the present, we are using the mathematical models, which are described in SNL documents, but in 'C' programming language. Engineering approach is more direct and an attempt has been made to generate insolation values for Mauritius, based on these formulations too, to serve some verification purposes. The full-scale implementation of SNL PV_LIB (Library of routines for simulation of photovoltaic energy systems), which provides a set of well-documented functions for performing a complete scientific analysis is likely to take at least another year or two.

1. Introduction

Generating spatial data, based on some of the well-established modeling techniques like those adapted by Sandia National Laboratories in conjunction with the SPA of NREL, has become an extremely powerful tool for every Nation, which is striving hard to use insolation figures as input to size solar power systems. Our main research endeavor is to generate Solar Resource Maps (SRP) [1,2] of Global Horizontal Irradiation (GHI), Direct Normal Irradiation (DNI) and Potential PV electricity production (PVOU) for Mauritius. The major advantage of developing such a unique tool is that it will then allow much finer graininess as and when we complete the calculations for every region of the country. The current authors have also established a linkage with both Central Electricity Board (CEB) of Mauritius and Ramgolam of University of Mauritius [3] and are participating with the latter in the data gathering efforts. We are also in the process of installing additional data gathering equipment at



various other locations in Mauritius. Ramgolam and Soyjaudah [3] have installed C-Si reference cells in three locations representing the North, middle-East and South of Mauritius. Data collected at these locations for the past 6 years are available (at intervals of 30 secs.) pertaining to global horizontal solar irradiance. We are now in a good position to incorporate high resolution data in the resource maps.

Switching our focus from data gathering to algorithms, we are aware of the several renowned mathematical models that researchers and engineers have been using to evaluate current performance (performance index). As part of a group activity in a workshop organized by Sandia in 2010 in Albuquerque, New Mexico, [4] PV professionals ranging from PV model developers, integrators, independent engineers to academia were tasked to predict system performance of a given well defined system using these established models. The captured predictions are depicted in figure 1. It can clearly be seen from the compilation of the outcome, that the existing software packages mostly (14 out of 21 cases) over-predicted the system performance. Horizontal line is measured energy.

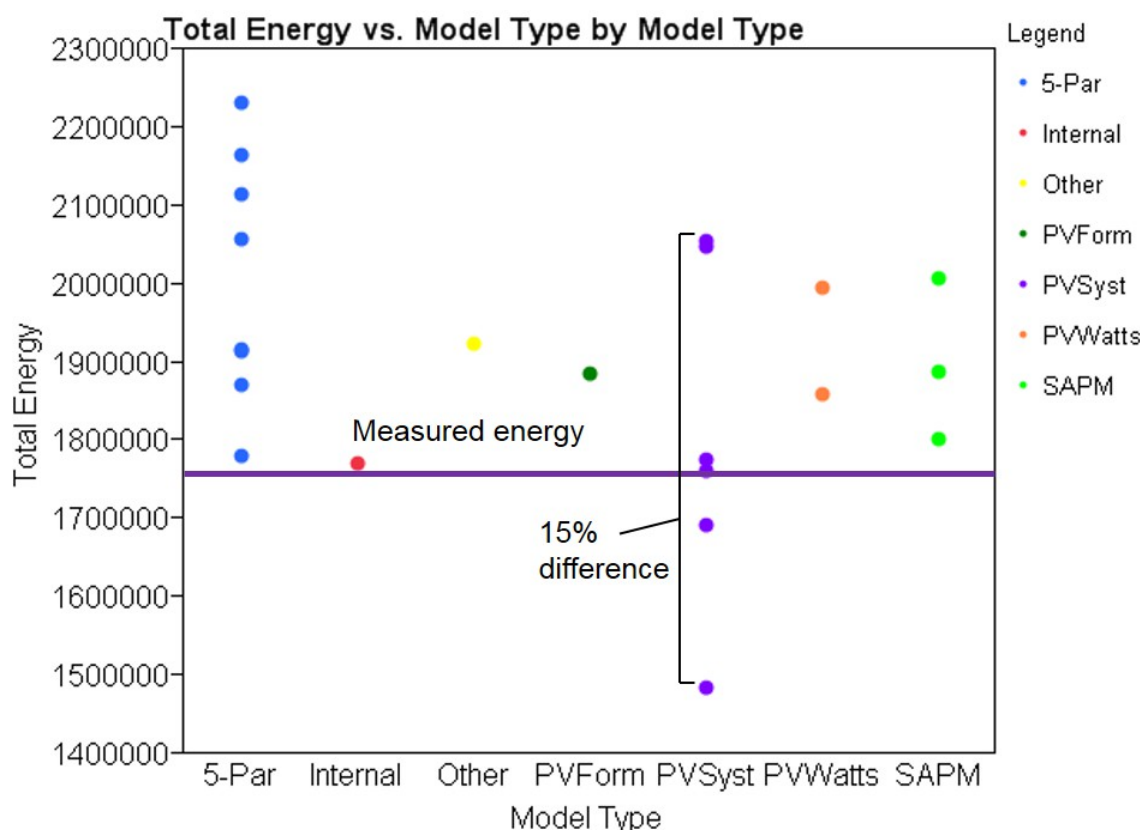


Figure 1. Example results of a blind modelling study that led to the idea to form the PV Performance Modelling Collaborative [4].

One of the most worrying aspect of this endeavour was that the variation of the results in no way related to the capability of the model which was used, but rather depended on the limitations of the individuals concerned indicating the lack of depth that a purely scientific approach can bring to the fore. Designers were always aware that a rigorous parameterization exercise must be carried out in order to provide all the input data that is required to appropriately set up the model, but unfortunately, these are not known with high accuracy, a priori. They depend not only on the solar panel characteristics, but also on the location details and weather conditions. In actuality, most of the models are devised by linking a collection of separate modelling algorithms. In short, PV performance models demand numerous inputs and judicious selection of sub-model choices must be fully accurate. Most of the uncertainties or variations in predictions are entirely due to the nature of these choices made by

model operators. Another important observation of Sandia was that the scientific understanding which forms the basis for PV system modelling algorithms is not easy to find. One has to search years of conference proceedings, journal papers and numerous internal reports to gather much of the information. These results and the apparent inconsistencies they produced, strongly indicated that there was an immediate need to form the Photovoltaic Performance Modelling Collaborative (PVPMC) and thus emerged the Sandia initiative.

Sandia [5] outlines 10 PV Modeling steps and has come up with a toolbox (PV_LIB) to facilitate the design of Solar Power Systems. The initial five steps are specific to solar design as they pertain to satellite generated atmospheric irradiance [6] and weather data, translation of irradiance to array of panels (includes orientation of the panel, beam and diffuse irradiation and ground surface reflections), shading and soiling, cell temperature and module output (IV curve). It uses complex mathematics, but the first step in this process is standardizing the SPA of NREL. A number of calculations are being done exploiting the accuracy and power of these packages for various Mauritius locations [7] (identified by their longitude and latitude) in order to estimate the angle of incidence variations with different date stamps. The ultimate goal is to treat the computational outcome as ‘big data’ and integrate this with the spatial analytics using the latest NoSQL tools, see Chandrasekaran [8].

2. Solar Position Algorithm (SPA) of NREL

The first step is to know the exact position of the Sun, vis-à-vis, various Mauritius locations, in order to ably exploit the energy from the sun, see [9,10] for an understanding of the basics of the Physics of the sun and the governing equations. Several factors influence the motion of the sun. The daily rotation of the earth about its north–south axis has to be superimposed on the seasonal north–south motion of $\pm 23^\circ 27'$ away from the equator. The fact that earth’s orbit around the Sun is elliptical and earth has an axial tilt, also need to be factored in as even the latter induces a subtle change in the sun’s noontime position.

As a first step, the components of the code developed were first downloaded for porting and compiled inside Eclipse Integrated Development Environment (IDE) tool. Each run required pre-processed input data pertaining to the location, details such as their global position and several other data computable from National weather data records. Our main focus is to calculate the zenith and azimuth angles of the Sun at these locations, as also the incidence angle, which determines the efficiency of solar energy absorption. The azimuth is counted starting from the north on the east, so that a star in the north has an azimuth of 0° , while a star in the east has an azimuth of 90° . Figure 2 depicts the measurement convention and azimuth varies from 0 to 360 degrees around the observer or the panel. The governing equations are also described, but they involve evaluating numerous intermediate values.

Figure 3 shows the characteristic variation of these angles relating to the observer stationed at the terrace of Université des Mascareignes (UDM) (with longitude of -20.243743° and latitude of 57.454765°). The pre-processor input data included both higher and lower refraction values as well as for two different date stamps. SPA requires average local pressure, local temperature, elevation, observer time zone (4 hrs. negative west of Greenwich) and the values for $\Delta UT1$ for correcting earth’s irregular rotation rate and ΔT have been calculated as per the following formulae, see bulletin [11] and see table 1. The last but one column lists the value for $\Delta UT1$ and all that we need to do is to look up for the particular date (first column).

$$\Delta UT1 = UT \text{ (Universal Time)} - UTC \text{ (Coordinated UT) in seconds.}$$

$$\Delta T = TT \text{ (Terrestrial Time)} - UT \text{ in seconds.}$$

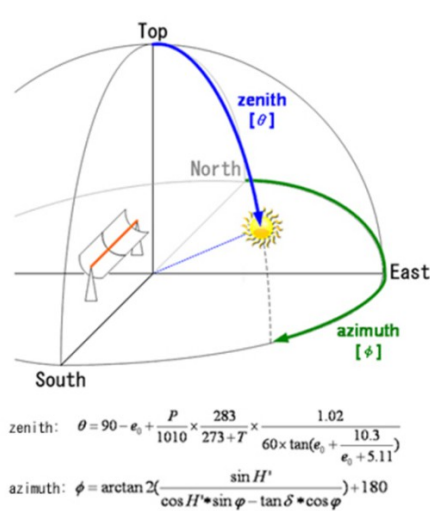


Figure 2. Convention for measuring zenith and azimuth angles [9]

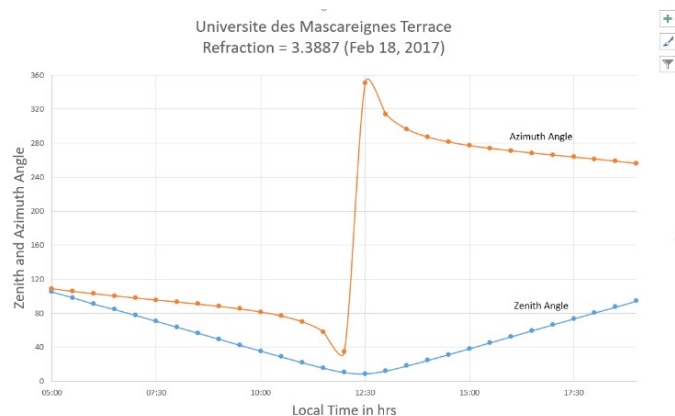


Figure 3. Variation of zenith and azimuth angles from sun rise to sun set as per our SPA computations.

Table 1. Combined earth orientation parameters [11] MJD is the Modified Julian Date. The first entry is for April 22, 2016. You need to look for entry corresponding to any particular date.

The contributed observations used in the preparation of this bulletin are available at <http://www.usno.navy.mil/USNO/earth-orientation/eo-info/general/input-data>. The contributed analysis results are based on data from very long baseline interferometry (VLBI), satellite laser ranging (SLR), global positioning system (GPS) satellites, lunar laser ranging (LLR) and meteorological predictions of variations in atmospheric angular momentum (AAM)

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SN	MJD	X "	error "	Y "	error "	UT1-UTC	error s
16 4 22	57500	0.02215	0.0000 9	0.45877	0.0000 9	-0.121971	0.000006
16 4 23	57501	0.02406	0.0000 9	0.46021	0.0000 9	-0.123587	0.000008
16 4 24	57502	0.02577	0.0000 9	0.46183	0.0000 9	-0.125140	0.000008
16 4 25	57503	0.02708	0.0000 9	0.463530	0.0000 9	-0.126528	0.000017
16 4 26	57504	0.02809	0.0000 9	0.46534	0.0000 9	-0.127823	0.000016
16 4 27	57505	0.02893	0.0000 9	0.46702	0.0000 9	-0.129037	0.000017
16 4 28	57506	0.02973	0.0000 9	0.46856	0.0000 9	-0.130372	0.000018

For calculating ΔT is the difference between the Earth rotation time and the Terrestrial Time (TT), the following equations have to be used. Refer to [12] for header file and nomenclature:

$$TT = TAI + 32.184 \text{ secs.}$$

$$UT = TT - \Delta T$$

$$\text{or } \Delta T = TT - UT$$

ΔT is the difference between the Earth rotation time and the Terrestrial Time (TT).

We Know: $UT = UTC + \Delta UT1$

Hence, $\Delta T = TAI + 32.184 - (UTC + \Delta UT1)$

Re-arranging terms we get:

$$\begin{aligned} \Delta T &= 32.184 + (TAI - UTC) - \Delta UT1 \\ &= 32.184 + 36 - (-0.130372) = 68.314372 \text{ secs.} \end{aligned}$$

Several other pre-processing calculations have to be done and table 2 lists some partial results for one refraction value.

Table 2. Partial SPA output.

Date	Time	Topocentric zenith angle	Top. azimuth angle (eastward from N)	Top. azimuth angle (westward from S)	Surface incidence angle	Local sunrise time	Local sun transit time	Local sunset time
4/28/2016	0:00:00	173.656300	196.984863	16.984863	173.656300	6.216369	12.12592 4	18.031630
4/28/2016	1:00:00	166.109590	113.808698	-66.191302	166.109590	6.216369	12.12592 4	18.031630
4/28/2016	2:00:00	152.530292	98.211254	-81.788746	152.530292	6.216369	12.12592 4	18.031630
4/28/2016	3:00:00	138.510214	91.270433	-88.729567	138.510214	6.216369	12.12592 4	18.031630
4/28/2016	4:00:00	124.446864	86.301702	-93.698298	124.446864	6.216369	12.12592 4	18.031630
4/28/2016	5:00:00	110.454874	81.830254	-98.169746	110.454874	6.216369	12.12592 4	18.031630
4/28/2016	6:00:00	96.620869	77.219734	-102.780266	96.620869	6.216369	12.12592 4	18.031630
4/28/2016	7:00:00	82.937453	71.980142	-108.019858	82.937453	6.216369	12.12592 4	18.031630
4/28/2016	8:00:00	69.894957	65.520388	-114.479612	69.894957	6.216369	12.12592 4	18.031630
4/28/2016	9:00:00	57.567039	56.936266	-123.063734	57.567039	6.216369	12.12592 4	18.031630
4/28/2016	10:00:00	46.630878	44.756585	-135.243415	46.630878	6.216369	12.12592 4	18.031630
4/28/2016	11:00:00	38.323313	26.994927	-153.005073	38.323313	6.216369	12.12592 4	18.031630
4/28/2016	12:00:00	34.603975	3.224226	-176.775774	34.603975	6.216369	12.12592 4	18.031630
4/28/2016	13:00:00	36.891097	338.527982	158.527982	36.891097	6.216369	12.12592 4	18.031630
4/28/2016	14:00:00	44.261344	319.160652	139.160652	44.261344	6.216369	12.12592 4	18.031630
4/28/2016	15:00:00	54.691376	305.791757	125.791757	54.691376	6.216369	12.12592	18.031630

	0						4	
4/28/2016	16:00:00	66.750794	296.490979	116.490997	66.750823	6.216369	12.125924	18.031630
4/28/2016	17:00:00	79.667504	289.621572	109.621572	79.667504	6.216369	12.125924	18.031630
4/28/2016	18:00:00	92.810686	284.164803	104.164803	92.810686	6.216369	12.125924	18.031630
4/28/2016	19:00:00	107.003960	279.477490	99.477490	107.003960	6.216369	12.125924	18.031630
4/28/2016	20:00:00	120.965675	275.071238	95.071238	120.965675	6.216369	12.125924	18.031630
4/28/2016	21:00:00	135.023029	270.397645	90.397645	135.023029	6.216369	12.125924	18.031630
4/28/2016	22:00:00	149.081849	264.374637	84.374637	149.081849	6.216369	12.125924	18.031630
4/28/2016	23:00:00	162.903624	252.941391	72.941391	162.903624	6.216369	12.125924	18.031630

While figure 3 is for a more recent date (Feb 18, 2017), figure 4 curves represent a time exactly 6 months before, but for the same location. Computations were also performed for yet another location (Mauritius Solar Power Plant at Bambous at a longitude of -20.261872° and latitude of 57.414653°), see figure 5. Some important output values that are invaluable for optimizing power plant system design like sun rise and sun set times and total transition time are listed in table 3.

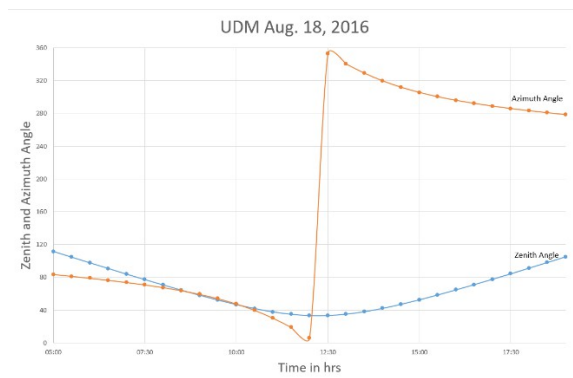


Figure 4. Variation of zenith and azimuth angles at UDM Aug 16 as per our SPA computations.

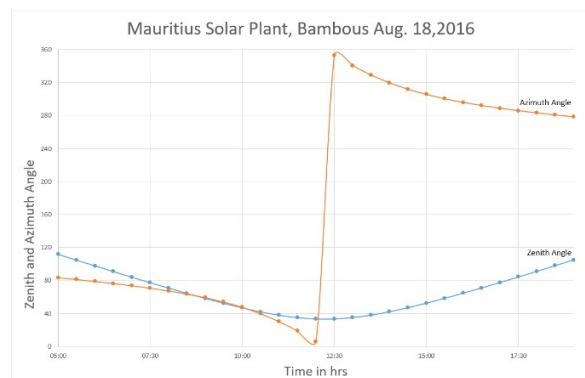


Figure 5. Variation of zenith and azimuth angles at Bambous Aug 16 as per our SPA computations.

Table 3. SPA outputs with different date stamps and locations (as per our computations).

No	Location	Date	Local sunrise time	Local sun transit time	Local sunset time
1	University Terrace	Feb 18, 2017	06:44	12:24	18:43
2	University Terrace	Aug 18, 2016	06:32	12:14	17:56
3	Bambous Solar Plant	Aug 18, 2016	06:31	12:31	17:57

A careful analysis of the output (including those not displayed here) lead to the following findings:

- The angle of incidence on the solar panel for various time and date stamps, had been found to be more or less the same as zenith angle and hence are not depicted in the curves.

- The characteristic curves are not influenced by variations in refraction values or altitude.
- Sun transit time is significantly high and as more calculations to follow are likely to indicate, the value remains high throughout the year. This will ensure steady high power generation capacity.
- The azimuth angle curve shifts slightly below (by about 30°) as we progress from February to August.
- The values of zenith angle at the time of sun rise and sun set are more or less the same (about 120°), whereas the value at noon is 6° (close to near vertical) in Feb as opposed to 34° in August. The value seems to be an invariant with location.
- Since zenith angle is the more important of the two parameters influencing the power generation capacity, our subsequent calculations, will give Mauritius, an excellent perspective on optimization.

It will be apparent to solar plant designers, who use the Sandia toolbox, that the factors mentioned under (ii) will play a major role in our subsequent calculations.

One of the problems we faced when our team was trying to design a grid connected PV power plant for our University was the restriction that were placed on us due to the effect on grid stability problem. It may hence be advisable to see how more developed countries like Germany approached this problem, see the next section.

3. The imperatives of adapting scientific methodologies for optimization of plant system design

Taking a look at the global scenario, which also is a pointer to the fact that grid stability and reliability issues are being tackled on a war footing, two examples one each from India and Germany are presented. India has already crossed the 300 GW energy production barrier with a recent addition of 28 GW of Wind Energy (that takes its World ranking to # 4 after China, USA and Germany) and 9 GW of Solar. In addition, 21 GW has been tendered for the ensuing year out of which 11 GW order has already been awarded. 31,472 Solar Pumps are installed in 2015-16 alone and this is higher than total number of pumps installed during last 24 years. The solar power plant licenses awarded so far for 2017 alone will surpass the entire capacity of all the nuclear power plants that are in operation in India including 6 others under construction! India is investing \$ 1.8 billion for dedicated transmission lines, to inter connect 34 solar parks situated across 21 states. By August, 2015, Germany recorded a share of 72% variable renewable energy in the German power system. The power system did not suffer any major reliability issues.

Figure 6 and 7 give a glimpse of some of the weather-related information that is required for the pre-processor input. The reason for selecting February (considered warm, but cloudy time of the year) and August, the coldest month, should become obvious now. For our computing requirement, we had accessed the source data base maintained by Mauritius Meteorological Services to ensure greater accuracy.

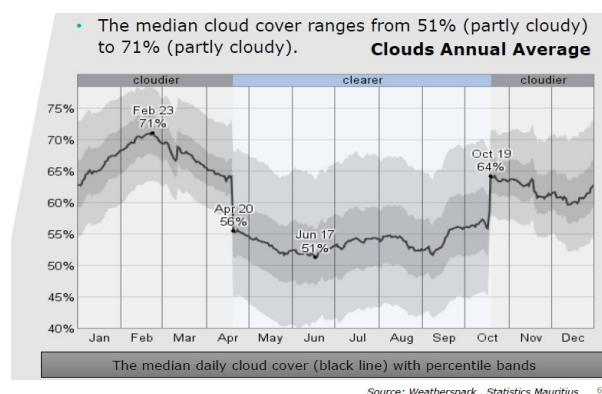
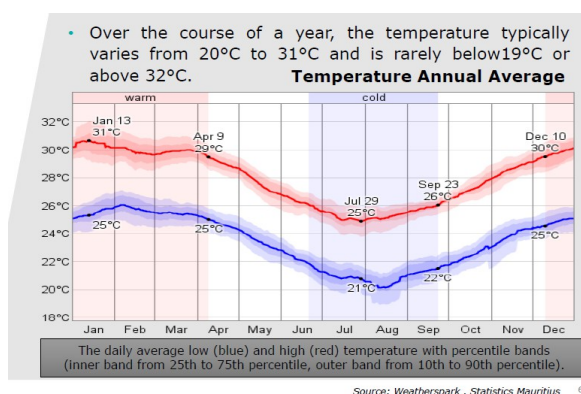


Figure 6. Daily low and high temperature variations for Mauritius.

Figure 7. Extend of Cloud cover for Mauritius (not for specific location).

The satellite data usually specifies that the average annual solar radiation arriving at the top of the earth's atmosphere is roughly 1366 W/m^2 [13,14]. The atmosphere attenuates the rays and at sea level, the maximum normal surface irradiance becomes about 1000 W/m^2 on a clear day.

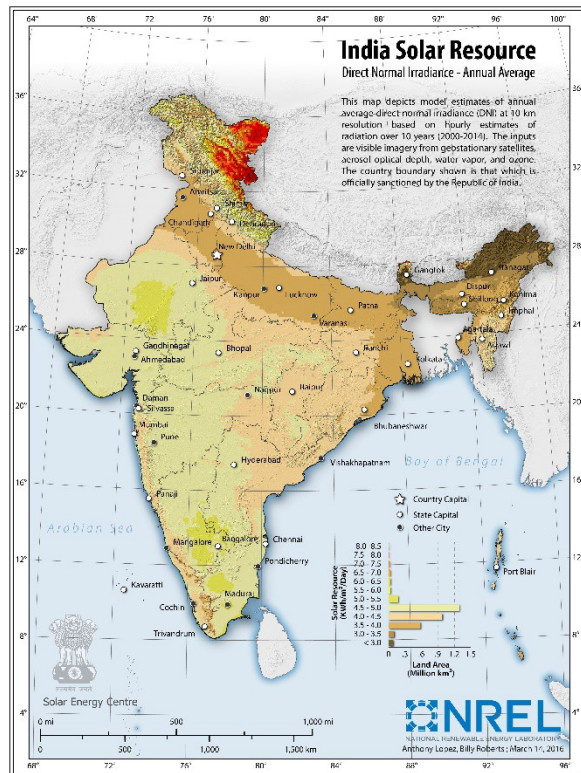


Figure 8. Detailed Solar Resource Map for India [15].

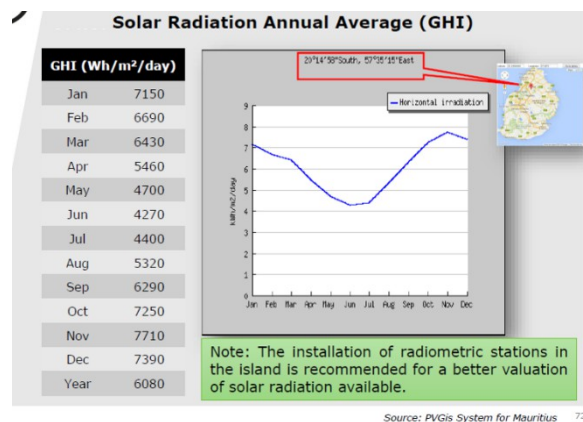


Figure 9. Solar Radiation Annual Average Map for Mauritius.

Insolation values for Indian states [15], see figure 8, like Gujarat, Rajasthan and Madhya Pradesh exceed even 2150 KW/m^2 (annual). Such authoritative maps are needed to be generated for Mauritius. Some values for radiation annual averages are available, see figure 9. The global practice is to develop for specific locations and with high accuracy. But the resource maps and data given for India and neighbouring countries were developed using weather satellite (METEOSAT) measurements incorporated into a site-time specific solar modelling approach developed at the U.S. State University of New York at Albany.

4. Sandia national laboratory toolbox

Irradiation and insolation bear a relationship that is similar to power and energy. Thus, while Irradiance is an instantaneous measurement of solar power over some area, insolation is a measurement of the cumulative energy measured over an area for a defined period of time (e.g., annual, monthly, daily, etc.). Both terrestrial and extra-terrestrial (without scattering) irradiance measurements can be carried out. Similarly, insolation measurements can be direct, diffused or total.

NREL SPA calculations have clearly established thus far that the angle of incidence drops by about 30° as we move from February to August. Figure 9 reinforces the validity, by depicting a dramatic

increase in Global Horizontal Irradiation (GHI) value per day from 5.320 kWh/m² to 6.690 kWh/m², during that period. The orientation of a solar panel with respect to the solar rays, is also a factor that determines its output. SPA data will provide a much better realistic estimate, as the solar collectors panels are almost always mounted at an angle towards the sun. Without this knowledge, we may be forced to adjust insolation estimates for winter (usual estimates will be lower) and summer. Many other implications include the effect of altitude on the estimates, which become more realistic with the scientific models.

Also observe that the panels are rated under standard conditions to determine the Watts peak (Wp) rating, which are not realistic. But the Sandia toolbox allows the designer to use Wp with insolation to determine the expected output, taking in to account factors such as tilt, tracking and shading to provide realistic values for installed Wp rating. At the outset, we also did some rough calculations using The Solar Electricity Handbook [16], please see figure 10. The calculations have been performed for one fixed wattage of the solar panel. The post processed output indicates that the changes in incidence angle with season has a greater bearing when the panel is kept horizontal, whereas a 20° tilt of the surface, alters the calculations completely. Hence, there is a need to optimize this angle by using more rigorous scientific tools like Sandia toolbox. The calculations are quite extensive, as one needs to perform for various locations and that too with varying time and stamp stamps.

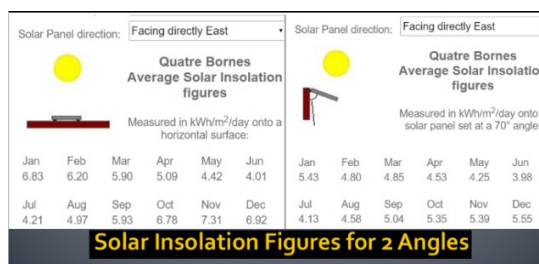


Figure 10. Insolation computations done using engineers' formulae [16].

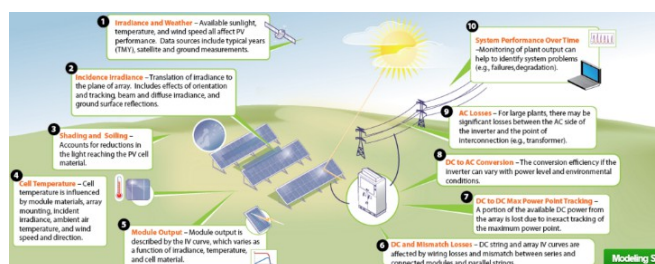


Figure 11. Ten steps analyzed by Sandia tool PV_LIB package [5].

Figure 11 describes the 10 steps that are involved in the PV Modelling Process. We will briefly touch upon some aspects, as a separate paper is being prepared to describe the implementation in greater detail. Estimation of Air Mass (AM), is an extremely crucial input that is required for pre-processor input. AM is a factor that defines and varies with the path of the sun rays as they travel to reach the earth's surface. For instance, if the sun is directly overhead (zenith angle = 0°), the air mass is equal to 1 at the mean sea level. As the angle of inclination of the rays gets larger, the rays traverse through longer distances resulting in an increase in the AM. One can also look at a situation when solar panels are placed at a higher elevation because of the terrain and in this case, the air mass value decreases with elevation. AM can be calculated as the inverse of the cosine of zenith angle, see figures 3, 4 and 5 for the variation of zenith angle obtained from NREL SPA.

For validation purposes, certain experiments were carried out at UDM using Model VA 200 Solar Module Analyzer made by Langlois France. Results from one of them lasting for an hour, in which the solar panel was kept facing North is shown in table 4 and figure 12. The toolbox contains procedure for employing piecewise decomposition models that are used to estimate DNI from measured GHI. Sandia uses three simple fitted models [18] developed from hourly average observations of GHI, DNI, and DHI. These models are based on the clearness index (k_t) and the diffuse fraction (k_d). These indices can be determined using equations $k_t = \text{GHI}/E_a$, where E_a is extra-terrestrial irradiance and $k_d = \text{DHI}/\text{GHI}$.

As the sun rays reach the earth's surface from extra-terrestrial to terrestrial, the amount of irradiance along the horizontal plane is denoted as GHI or Global Horizontal Irradiance. Pyranometer is used to measure GHI values. These values vary as cosine of the incident angle of the beam. Licor

LI-200 pyranometer [19] use a photovoltaic device with a diffuser to measure GHI. If a photovoltaic reference cell, the response function becomes different than a true cosine response.

Table 4. Data obtained from solar module analyzer at UDM.

North				Date	Time	Remarks
15 ⁰	20 ⁰	25 ⁰	30 ⁰			
Power peak (W _p)						
165	170	85.47	36.98	03/02/2016	11hr00	Sunny
42.19	33.57	35.12	26.54		11hr05	Rainy
35.75	28.13	31.93	52.1		11hr10	Rainy
24.9	21.1	22.25	31.55		11hr15	Sunny
69.3	76.07	99.88	164.9		11hr20	Cloudy
29.2	44.65	98.02	44.25		11hr25	Cloudy
58.36	64.27	63.43	180.6		11hr30	Cloudy
201.8	81.66	180	182.7		11hr35	Sunny
111	44.92	38.4	38.14		11hr40	Cloudy
114.9	87.19	44.53	37.33		11hr45	Sunny
165	95.28	66.11	57.72		11hr50	Sunny

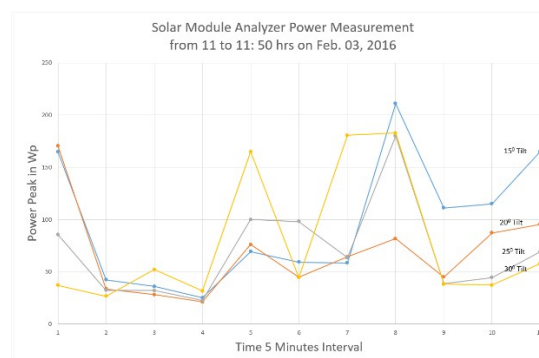


Figure 12. Depiction of the output values.

5. Conclusions

In summary, it should be stated that the advantages the solar energy systems can be exploited by every region (both small and big) of the country. That is why it becomes important that we are able to create a repository of data and information in the form of maps for every part of the country in order to facilitate and optimize renewable energy planning and siting. One would also like not only the big energy plant investors, but every other keen enthusiast, be it the scientist, engineer or general public to benefit by participating actively in this newly emerging field. It has strongly been suggested that we

follow the leads of the approach followed by leading technology nations and develop such Resource Data Centers for Mauritius too. The centers should host detailed resource information and provide all necessary design tools. A number of algorithms and packages in toolbox are being tried out to test their relevance to Mauritius. Initial calculations seem to indicate that they are extremely useful tools for providing greater insight. NREL hosts detailed solar resource maps, including for India. Our current attempt and the tools being developed should help us to fulfil this objective for Mauritius.

This brings us to the interesting aspect of embracing big data technology with an emphasis on spatial distribution operating in conjunction with Google Maps. Considering the fact, almost every development that will occur in this field will be futuristic and Innovations are likely to be fast tracked due to developments in several other fields, we are also looking to extend our research activities to cover several applications involving spatial analytics. The focus will be on NoSQL (Not only SQL) database servers connecting with commercial CARTO products. The link is provided by the location value expressed as latitude and longitude.

Designers and researchers will derive more benefit if they use scientific models to obtain data relating to weather and other solar energy related parameters as is being recognized as one of the most important steps in PV performance modelling. When the power system designer uses commercially available software packages for PV modelling, they usually start with historical data that has been compiled especially for solar applications (e.g., NSRDB, TMY). These design results cannot be completely relied upon for making decisions pertaining to investment, as they are not that reliable. These historical data need to be rechecked with scientific model-based data. These will include satellite data and site-specific ground measurements too. Our endeavour is to continue with this hybrid approach.

Acknowledgment

The authors express their profound thanks to Dr. Radhakrishna Somanah (Dinesh), Director General, UDM, Dr. Vijayen Valaydon, Ag. Dep D. G., UDM, (currently Mauritian Ambassador to France), Director, Ministry of Education and Human Resources, Tertiary Education and Scientific Research, fellow colleagues and students at UDM. The authors are most grateful to Dr. Grigorios L. Kyriakopoulos, School of Electrical and Computer Engineering at National Technical University of Athens (NTUA), Greece for a number of suggestions, which enabled us to carry out a major revision of the original manuscript to bring it to the current form.

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