The impact of atmospheric conditions on the sustainability of a PV system in a semi-arid region: A case study from South Africa

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***Abstract*—Varying atmospheric conditions can exert a significant negative impact on the amount of energy that is produced by a photovoltaic solar system. The purpose of this research is to present empirical data contrasting the available daylight hours of two distinct sites in South Africa, one being a semi-arid region and the other a pollution intensive area. Daylight hours are defined in this paper as the amount of time in which energy equivalent to the STC conditions is being received by a PV module. Both these sites are reported to have the same annual global horizontal irradiation according to available sources. However, the empirical data from this study indicates an average difference of 53% between the daylight hours available for the two sites for March, April and May.**

Keywords—irradiation, design,

I. Introduction

"The grand aim of all science is to cover the greatest number of empirical facts by logical deduction from the smallest number of hypotheses or axioms." These words, by Albert Einstein, are also true regarding the design and implementation of photovoltaic (PV) systems. In many cases, designed PV systems fail to prove sustainable due to a lack of real empirical data being applied.

However, the sustainability of PV systems is of paramount importance, especially in rural communities. This is due to its influence on the quality of life and on the "useful life" of the system's components. Quality of life concerns individual (physical and psychological health), interpersonal (social relationships) and contextual (environment) aspects [1], resulting in a tripartite classification. However, all three of these aspects are interrelated, with one have a bearing or influence on the other. For example, an individual's physical and psychological health is particularly threatened by their living conditions [2] (part of contextual aspects) which in turn impact on one's social relationships (interpersonal aspects). A sustainable rural PV system will enable individuals to function effectively within a set routine, as no unforeseen failures or power interruptions occur that may contribute to stress or anxiety. Additional stress on PV system components will also not result if sustainability is ensured. This prevents a reduction in the time line of the common "bathtub curve", which is widely used in reliability engineering to illustrate the "useful life" of components and systems.

However, some PV installation designs do not take into account the effect that varying atmospheric conditions have on the sustainability of a designed system. On the other hand, some simulation packages used for PV system designs do not always factor in extreme atmospheric conditions. Many of these climatic disturbances are often caused by El-Nino [3], that is known to be irregular and aperiodic [4]. There is also a need for more empirical data to inform variables within various simulation models [5].

The purpose of this research is to present empirical data that highlights the contrast between the available daylight hours of two distinct sites in South Africa, one being a semi-arid region and the other a pollution intensive area. These results highlight the need to consider more closely empirical data from prospective installation sights in order to verify simulation models. Firstly the importance of PV sustainability is discussed, where after the research sites are brought into context. The practical experimental setup then follows with the research methodology. The results are presented as quantitative data (descriptive statistics) followed by the conclusions.

II. PV Sustainability

The sustainability of a PV installation is dependent on many factors, including varying atmospheric conditions [6], choice of system components [7] and available solar recourses [8]. Using incorrect or low efficiency components can cripple a PV system under fluctuating atmospheric conditions, which include clouds, dust and air pollution [9]. These conditions can severely limit the amount of energy generated by a PV system, thereby influencing its effectiveness and life span of its energy storage system [10]. Empirical irradiation data has the potential of ensuring that a PV system is designed to maintain an adequate state of charge of its storage system given available solar resources. Sustainability can therefore be enhanced by using valid empirical data and quality components that are highly efficient and reliable.

III. Research Context

South Africa has some of the best solar radiation resources in the world, where the average daily solar radiation varies between 4.5 and 7 kWh / m^2 [11]. Fig. 1 illustrates this where the area between Bloemfontein and

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Johannesburg (which includes Vanderbijlpark) enjoys annual solar radiation of between 8000 and 8500 MJ/m^2.

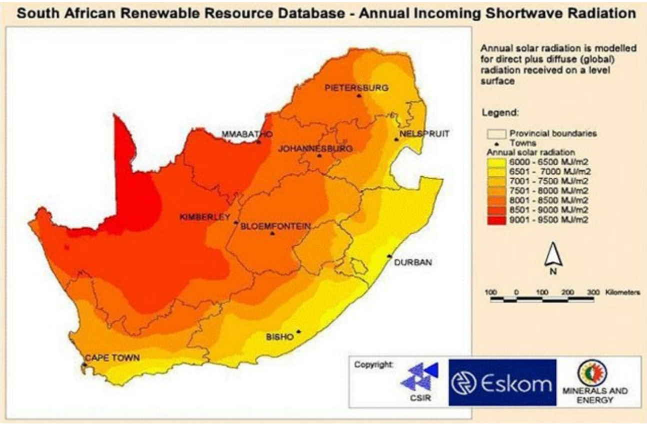

Fig. 1. Annual solar radiation for South Africa

The research context of this study is restricted to these two sites, namely Bloemfontein and Vanderbijlpark. They are separated by a distance of 370 km, which suggests that they each have their own unique atmospheric conditions.

In the heart of South Africa lies the Free State province with Bloemfontein as the provincial capital. The main campus of the Central University of Technology (CUT) is located in Bloemfontein and serves as one of the installation sites for this study. Bloemfontein is a semi-arid region (82% of South Africa is classified as such a region [12]) with a daily average global horizontal radiation of 5.15 kWh / m^2 / day [11]. Annual rainfall in Bloemfontein is around 378 mm [13] with the majority of rain falling in the summer months and water restrictions being imposed during the winter season (See Fig. 2). Localized dust storms often occur in late winter due to open pan surfaces and large agricultural lands [14]. These conditions are typical of arid and semi-arid regions, which are often characterized by water scarcity, hot dry weather, large areas of poor soils [15] and dust storms [16]. Midday temperatures may reach as high as 35°C in December, as shown in Fig. 3.

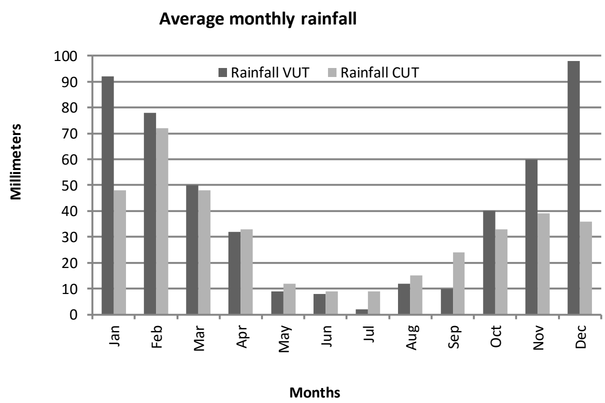

Fig. 2. Average monthly rainfall for VUT and CUT [13, 17]

On the other hand, Vanderbijlpark (part of the Vaal Triangle) is characterized by severe air pollution and Highveld thunderstorms. The declaration of the Vaal Triangle as a priority area was published in the Government Gazette of 2006 (Notice No. 365) in terms of Section 18(1) of the National Environmental Management: Air Quality Act of 2004. It was the first priority area in South Africa to be declared due to the concern of elevated pollutant concentrations within the area [18]. This results primarily from a large coal fired power station [19], many industrial companies (such as steel and chemical manufacturers) and various informal settlements around the Vaal Triangle that rely heavily on low quality coal as an affordable source of household fuel [18]. Annual rainfall for Vanderbijlpark is around 491 mm with the majority falling during the summer period (from November to February). The Highveld, which encompasses the Vaal Triangle, is well-known for its spectacular thunderstorms during this period [20]. Cloud movement is therefore a regularly occurrence in the Vaal Triangle, for at least seven months of the year (considering rainfall above 30 mm per month).

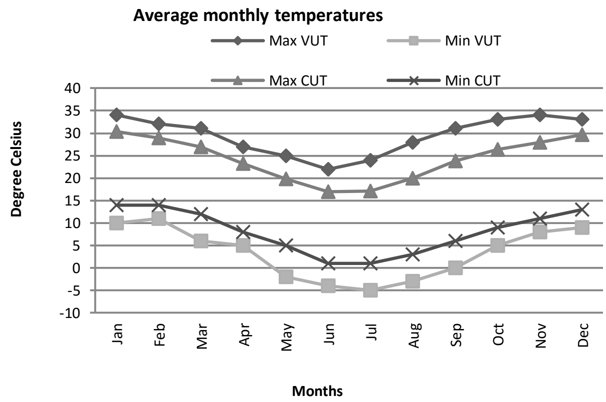

Fig. 3. Average minimum and maximum temperatures for VUT and CUT [17, 21]

The average yearly difference in rainfall (113 mm) and maximum temperature (5°C) further suggests that these two sites have varying atmospheric conditions, despite evidence pointing to similar annual solar radiation values. The rainfall pattern is especially important in the design of PV systems, as it is an indication of the interruption of direct beam radiation from the sun. This in turn spells a reduction in the available daylight hours required by a PV module to effectively charge an energy storage device, such as lead-acid batteries, which are used in PV systems.

The variance in rainfall and temperature, as well as the diverse atmospheric conditions, has given rise to a wide variety of simulation and mathematical models for the purpose of ascertaining the viability and reliability of solar energy production for a given region of the earth. Many of these isotropic or anisotropic based models make use of data collected from pyranometers, which are used to measure global solar radiation (sum of direct and diffused radiation [22]) at a specified location. However, research has shown that some widely used pyranometers strongly underestimates global radiation, particularly in winter, unless appropriate corrective measures are taken [23]. Other types of measurement problems also exist, such as those involved in the indirect determination of direct or diffuse irradiance, and in shadow band correction methods. All these factors point to the necessity of acquiring reliable empirical data of actual PV systems which have been installed in specific locations. The practical setup of such a PV system with data recording abilities which was used at CUT in Bloemfontein is presented in the following section.

IV. PRACTICAL SETUP

The practical setup at CUT consists of three identical PV systems, each comprising a 10W polycrystalline PV module, a 5A solar charger, a 20Ah battery and a 5W LED load (see Fig. 4 for a block diagram of a single system). All three systems are interfaced with an Arduino board (controlled by LabVIEW software) using a singular data logging interface circuit. This circuit has been reported on by a number of researchers [24-26] and provides power conditioning between the PV system and the data logging system (Arduino and LabVIEW).

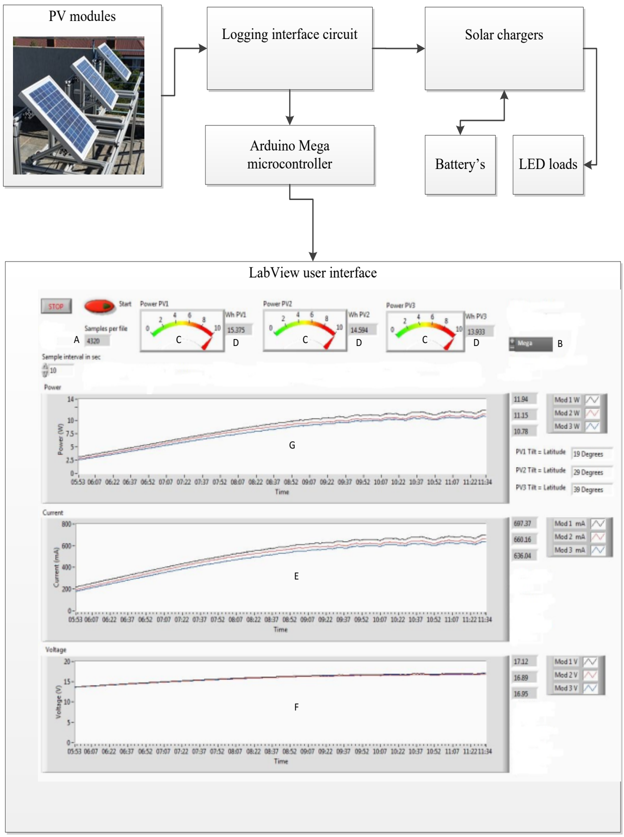

Fig. 4. Experimental setup

The three PV modules were mounted onto an aluminum frame and initially set to the same tilt angle equal to the Latitude of the installation site. The output power of these modules was then recorded and analyzed over a four week period resulting in a coefficient of variation of 1.4%. This coefficient of variation is calculated using the standard deviation and mean of the collected data. This was done to calibrate all three systems to a standard reference, thereby ensuring the validity and reliability of all subsequent measurements. The modules of the identical PV systems were then set to three different tilt angles as listed in Table 1, based on previous research. It must be noted that empirical data from only one PV system is presented in this paper, as all three PV systems would be exposed to the same atmospheric conditions and have the same daylight hours.

TABLE I. THREE DIFFERENT TILT ANGLES BASED ON RESEARCH DONE BY HEYWOOD [27] AND CHINNERY [28]

Author	**Equations of latitude**	**Tilt angle for Bloemfontein**	**Time period used**
Heywood	φ − 10°	29° − 10° = 19°	Summer
Heywood	φ	29°	Autumn / Spring
Chinnery	φ + 10°	29° + 10° = 39°	Winter

Daylight hour data was used in a simulation program developed in LaBVIEW to verify the sizing of the PV array and battery capacity necessary to ensure the sustainability of a PV system which could be installed at both sites. From the user interface, a user can set the amount of daylight hours, array size, dust and mismatch factor, charge controller efficiency, battery efficiency, inverter efficiency, and wiring losses (see Fig. 5). The load profile that is used in the simulation is loaded from an external text file that contains a typical load profile for a 24 hour period. Reasons for using the LabVIEW software in conjunction with an Arduino board are substantiated in the following sections.

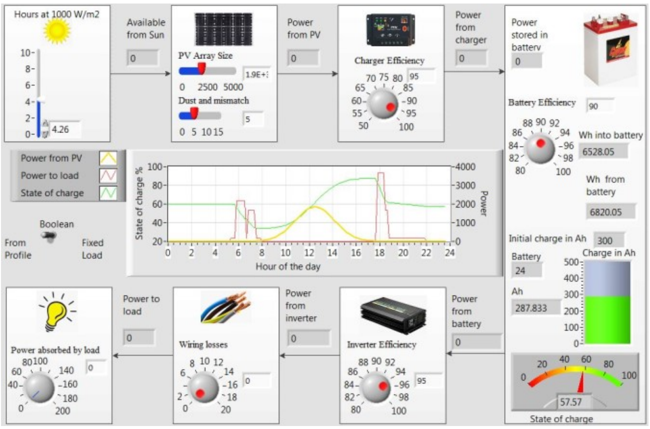

Fig. 5. User interface of LabVIEW simulation that was designed by authors and used in this research

A. LabVIEW

National Instruments LabVIEW is a graphical programming language that has its roots in automation control and data acquisition. It is a graphical representation, similar to a process flow diagram, which was created to provide an intuitive programming environment for scientists and engineers. The language has matured over the past 20 years to become a general purpose programming environment. LabVIEW has several key features which make it a good choice in an automation environment. These include simple network communication, turnkey implementation of common communication protocols

(RS232, GPIB, etc.), powerful toolsets for process control and data fitting, fast and easy user interface construction, and an efficient code execution environment [29].

B. Arduino board

The Arduino board is an electronic platform designed to simplify the process of studying digital electronics [30] and consists of a microcontroller, a programming language and an Integrated Development Environment (IDE) [31]. Arduino was born to teach Interaction Design, a design discipline that puts prototyping at the centre of its methodology [32]. The designers attempted to design a user-friendly software and hardware interface, making freely available the necessary documentation to support it [33]. The Arduino board and its associated components are very cost-effective in South Africa (around $70) when compared to other data logging devices.

V. Research Methodology

The purpose of this research is to present empirical data contrasting the daylight hours of two distinct sites in South Africa, one being a semi-arid region and the other a pollution intensive area. Although these sites are separated by 370 km from each other with their own unique climatic conditions, they both have the same annual solar radiation of approximately 2000 kWh / m^2. Data from the pollution intensive area (VUT in Vanderbijlpark) was published in 2011 and represents the time period of March through May of 2011. Data from the semi-arid region (CUT in Bloemfontein) was collected in 2015 (March through May) by using an experimental research design where a PV module was set to a tilt angle of Latitude +10°, which contributes to the maximum output power of the PV module for this region. Although the calendar years differ, the general atmospheric conditions for March through May for these sites have remained similar over the past few years (annual rainfall and ambient temperature data for the two sites have been correlated in this regard).

Watt hours (Wh) were recorded over a 3 month period at CUT's main campus in Bloemfontein, which correlates to the original month period of the VUT study (although not the same calendar year). This data was obtained by multiplying the voltage readings with the current readings obtained from the Arduino board for a given hour. Voltage measurements are obtained from a voltage divider network (147 kΩ resistor in series with a 100 kΩ resistor) which is then multiplied by a predetermined factor to obtain the actual physical value. Current measurements are obtained by measuring the voltage across a low value precision resistor (10Ω 10W 1%) and then multiplying it by a predefined factor to obtain the actual physical value.

The Wh data was then converted to daylight hours at STC and correlated to the global horizontal irradiation (obtained from a Kipp and Zonen CMP11 un-shaded pyranometer) measured for Bloemfontein from March through May of 2015 which corresponds to the early winter season for the installation site. This was done in order to validate the collected data. The available daylight hours for March through May of 2011 (data from the pollution intensive area in Vanderbijlpark with Latitude: 26°42'37.91" S and Longitude: 27°51'39.35" E) was then correlated to the empirical data for March through May of 2015 (data from the semi-arid region in Bloemfontein with Latitude: 29°07'16.78" S and Longitude: 26°12'45.95" E). Daylight hour data from both sites was then used in a simulation program developed in LaBVIEW to verify the PV array and battery storage size necessary to supply a specific load profile (see Fig. 5). A generic load profile for a single household was used in the simulation model where the maximum energy was consumed between 06h00 and 08h00 in the morning and around 18h00 in the evening. All the system parameters were kept the same and only the array sizes were changed to compensate for the difference in daylight hours for the two sites.

VI. Results and Discussion

Data from VUT was obtained from previous research that was done from March to May 2011. The average daylight hours for VUT and CUT are shown in Fig. 6. According to data from Fig. 1, both VUT and CUT should have a total annual irradiation of 2000 kWh/m^2. However, this is not evident from the results shown in Fig. 6. A big difference exists in the recorded daylight hours between the two sites with an average of 4.74 hours for VUT and 7.09 hours for CUT. The daylight hours for CUT are much higher than those for VUT which can be due to the fact that VUT is situated in a pollution intensive area and enjoys a higher rainfall per annum, resulting in more cloud cover for the recorded time period.

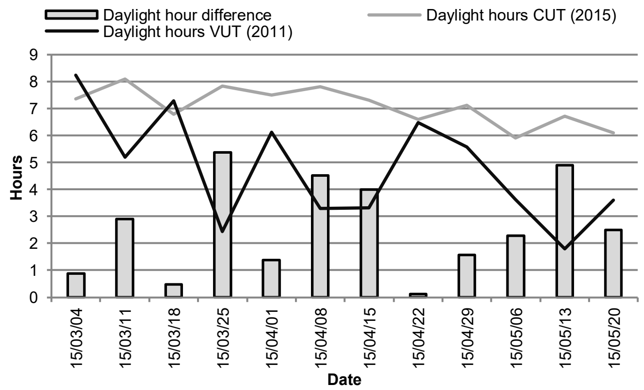

Fig. 6. Recorded STC hours for CUT and VUT from March to May

Validating the empirical data obtained from CUT (being the STC daylight hours) required correlating it to the average hourly global horizontal irradiation obtained from a pyranometer. Fig. 7 presents this correlation where a similar pattern is observed between the two data sets with a correlation of 71%.

The different STC daylight hours for the two sites were then used to calculate the required PV array size for a sustainable renewable energy system. This practical application of the empirical data enhances the reliability and sustainability of a proposed PV system for these sites. The simulated PV system comprises a solar charger (95% efficient), a 500Ah battery bank (90% efficient) and an inverter (95% efficient). The dust and mismatch factor that was used was set at 5% with a 8% overall wiring loss. A load profile with peaks between 06H00 and 08H00 in the morning and 18h00 in the evening was used. The system components, other than the array itself, were kept constant for both the simulations. In order to ensure a state of charge of at least 60% in the 500Ah battery after a 24 hour period required a 1900W PV array for VUT (4.74 STC daylight hours used). For CUT, with 7.26 STC daylight hours, a 1300W PV array would be required.

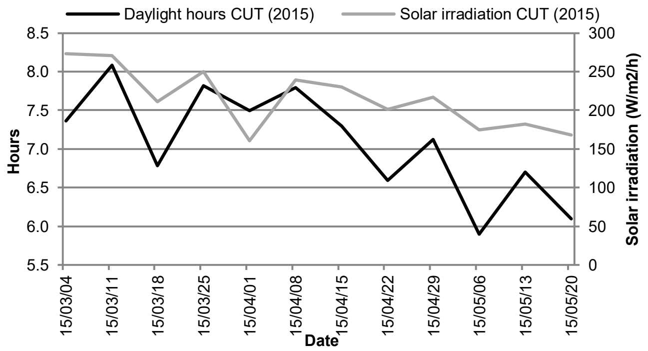

Fig. 7. STC daylight hours for CUT compared to the global horizontal solar irradiation for Bloemfontein

VII. Conclusions

The purpose of this research was to present empirical data contrasting the daylight hours of two distinct sites in South Africa, one being a semi-arid region (CUT) and the other a pollution intensive area (VUT). Although these sites have a similar global horizontal irradiation level, significant varying atmospheric conditions exist. Different rainfall patterns exist along with different ambient temperatures. The results of this study have further shown a significant difference between the two sites in terms of their STC daylight hours (4.74 hours for VUT and 7.26 hours for CUT). Moreover, the simulation model indicated a PV array size difference of 600W between the two sites. Taking these differences into account, as well as considering real empirical data, may contribute to the design and installation of PV systems that are sustainable despite varying atmospheric conditions.

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