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Ambient Temperature and Relative Humidity Impacts on a Photovoltaic Module under Niamey Climatic Conditions

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ABSTRACT

This paper presents the effect of ambient temperature and relative humidity on a monocrystalline solar module installed on the rooftop tilted with an angle of 15° facing South. The output current, and voltage for the photovoltaic module were measured every thirty minutes and also the ambient temperature around the PV module. In addition to these field tests data, solar radiation data from a pyranometer installed in CNES for the same angle and the same environment was used to estimate the conversion efficiency of the module. Also, the relative humidity data obtained from NASA power agroclimatology website for the same period were used. Results show that there is a negative correlation between the ambient temperature and the conversion efficiency and between the relative humidity and the PV energy output. Indeed, the slope between the ambient temperature and the conversion efficiency is estimated to be-0.49%/°C and the one between the relative humidity and the PV energy is -4.3Wh/m^2.

1. Introduction

The renewable energy resources are becoming the mainstream energy resource (Twidel & Weir) [1]. Among these renewable energy resources, the solar photovoltaic (PV) is the most promising resource. Indeed, PV production has been increasing by an average of 20% each year since 2002, making it a fast-growing energy technology. However, in 2009, the global cumulative PV installations have exceeded 21 GW Martinot et al.) [2].

However, the country is endowed with high potential renewable energy. According to solar map for Africa, the country has on average a daily radiation ranging from 6 to 7.5 kWh/m^2/day. This high potential in solar energy is underused. Still in 2012, the total installed PV capacity was over 4 MW with 2772 kW for telecommunications, 913 kW for water pumping, 199 kW in health sector, 88 kW for household, and 70 kW for education centre

Nevertheless, there is growing investment interest in PV grid connection and standalone system as the falling cost of PV in recent years brings the technology closer to grid parity in many parts of the world. Niger’s high electricity generation cost is likely to provoke investor interest in introducing PV to the grid. Also policy makers in Niger widely acknowledge the important role that renewable energies can play in developing the power sector. Solar PV energy is being promoted as reliable energy source that can contribute to reducing dependence Vis à Vis the imported electricity from Nigeria (Singh) [3].

So in order to efficiently and economically use the photovoltaic solar energy, there is a need to study the environmental parameters that can negatively impact on its performance and to see how best one can reduce these impacts. Indeed, the solar modules are rated under standard test conditions (STC, irradiation=1000W/m^2, Tc=25˚C, AM1.5) (Bucher) [4]. These conditions are different outdoors. So studying the impact of ambient temperature and relative humidity on the photovoltaic performance is of great important in a hot climate like Niamey. Studying the impacts of ambient temperature and relative humidity has been done in some parts of the world (Fesharaki et al.; Mekhilef et al.; Sanusi et al.) [5, 6, 7]

Indeed, the performance of solar photovoltaic module is site specific.

The objective of this paper is to study the impact of temperature and relative humidity on the performance of the PV module and estimate the daily energy output of the module under the environmental conditions of Niamey

2. Theory behind solar photovoltaic energy

The sun is the most significant source of renewable energy. The photovoltaic cell is a semiconductor device that converts directly the sunlight to electric power. In general, any element that converts sunlight into electricity is called PV device (Singh) [3]. Solar energy can be converted into electricity through two mature technologies, the solar PV technology and the Concentrating Solar Power (CSP) technology.

CSP systems use mirrors or lenses to concentrate a large area of sunlight, or solar thermal energy, onto a small area. Electrical power is produced when the concentrated light is converted to heat, which drives a heat engine (usually a steam turbine) connected to an electrical power generator.

The direct conversion of solar energy into electrical energy is performed by means of photovoltaic (PV) generators.

Generally, the term photovoltaic effect refers to the generation of a potential difference at the junction of two different materials in response to visible or other electromagnetic radiation. Thus, the broad study area of solar energy conversion into electrical energy is denoted as photovoltaic.

2.1 Solar energy conversion

The basic process of solar cell is the generation of an electron-hole pair as a result of absorption of visible light or other electromagnetic radiation by a semiconductor material.

Before this process takes place the energy of the photon must be greater or equal to the energy gap of the cell, which is 1.1eV for the case of silicon. For the photons with energy less than the energy gap, no electron-hole pair is generated. Global solar radiation comprises the direct radiation also called the beam radiation, the diffused radiation and the reflected radiation.

2.2 Photovoltaic cell operation

A PV cell is a semiconductor p-n junction photodiode that can generate electrical power when exposed to light (Said et al.) [8].

The principal operation of a PV cell is based on the phenomenon termed as the photovoltaic effect. The photovoltaic is a combination of the Greek word phos, photos (light, of the light) and the name of the Italian physicist Alessandro Volta (1745-1825). He, discovered the first functional electro-chemical battery and the unit of electricity, Volt is named after him. Hence, the photovoltaic effect means the generation of a potential difference at the junction of two different materials in response to visible light or other radiation. The basic processes behind the photovoltaic effect are:

- Generation of the charge carriers due to the absorption of photons in the materials that form a junction,
- Subsequent separation of the photo-generated charge carriers in the junction,
- Collection of the photo-generated charge carriers at the terminals of the junction.

2.3 Modelling of PV devices

2.3.1 Ideal PV cell

To simplify the analysis of PV cells in electrical circuits, an electrical model of a PV cell is introduced. Thus the equivalent circuit of an ideal PV cell is shown in the figure 1.

It consists of a current source driven by sunlight and an ideal diode. The equation based on the theory of semiconductors that mathematically describes the I-V characteristics of an ideal PV cell is given by the following equation:

$$I = I_{Ph} - I_{sat} * [e^{(\frac{q(V+IR_S)}{nkT}} - 1] \qquad (1)$$

The equivalent circuit is shown in figure 1 [9]

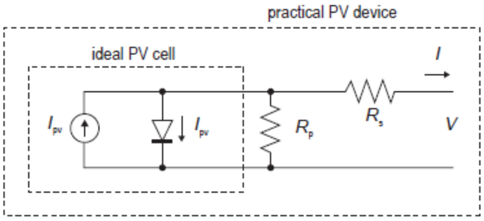

Figure -1: Single-diode model of ideal PV cell and Equivalent circuit of practical PV device

Since a single PV cell is generating relatively small output voltage and a relatively high current, multiple cells are connected in series and enclosed in a common frame to form a photovoltaic panel or module.

By connecting many cells in series, the voltage of the PV module is increased and the conduction losses in the cables are minimized. A PV module represents the basic building block for large scale PV power production. Multiple PV modules can be stacked in series forming strings of modules. As a result, the voltage increases.

By connecting multiple strings in parallel, PV arrays are formed. For an array to perform well all the modules must not be shaded. Otherwise it will act as a load resulting in heat, which may damage the solar cell. By pass diodes are used to avoid damage, however resulting in a cost increase. Integration of bypass diodes in some large modules during manufacturing is not uncommon and reduces the extra wiring required (Villalva et al.) [9].

2.4 Factors affecting the performance of the output of **solar** *photovoltaic*

2.4.1 Irradiance

The current-voltage (I-V) and the power-voltage (P-V) depend on the climatic conditions. The output power of the PV module produced depends on the irradiance on PV characteristics is shown in the figure 2below :

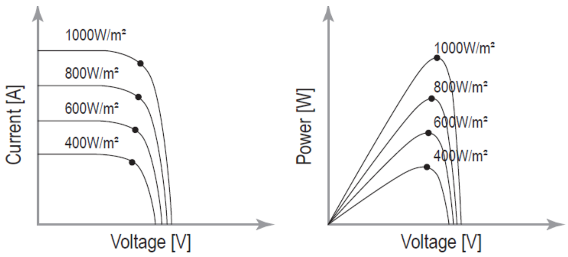

Figure 2: Irradiance effect on PV characteristics (Rekioua) [10]

Hence, with the increase of irradiance we have both increases of I-V and P-V characteristics. The power of the PV module increase with increase of irradiance up to a certain value of the voltage before it starts decreasing.

2.4.2 Temperature

Temperature is a physical quantity characterizing the mean random of molecules in a physical body and represents the thermodynamics state of it. The temperature units are divided into two categories: absolutes and relatives. The former have the lowest theoretical possible temperature: the absolute zero as reference and kelvins degrees is the unit. The latter compare a fixed physical-chemical process that always happens at the same temperature; the most used relative unit is the Celsius degrees. It is the most used for the meteorological purposes. This measurement unit is defined by choosing the water freezing point to be 0ºC and the water boiling point to be 100ºC.

When the temperature increases, the short circuit current increases while the open circuit voltage strongly decreases. The output power of the module decreases. In real life situations especially in Sahelian countries where the ambient temperature is higher, the internal temperature of the modules and consequently the efficiency of the PV module is lower. The data for April, May, June, and July are considered to assess the effect of the temperature on PV module in this study. The figure 3 below shows the effect of temperature on the PV characteristics

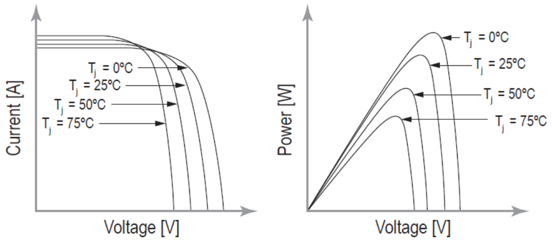

Figure 3: Temperature effect on PV characteristics (Rekioua) [10].

3. Materials and Methods

Knowledge of the local solar-radiation, ambient temperature, and relative humidity is essential for the proper design of building energy systems, solar energy systems and PV solar technologies.

This section will describe briefly the study area, its available solar radiation, ambient temperature, and the relative humidity of the Study area.

Two sites located in Niamey have been considered for this work. The national center for solar energy (CNES) where global radiation is collected from a pyranometer with a dataloger and the roof of of the wascal's building where the PV power is measured each 30 minutes. This site has been choosen in order to avoid any perturbations. (such as shading, animals, people….).
The two sites are shown in figure 4.

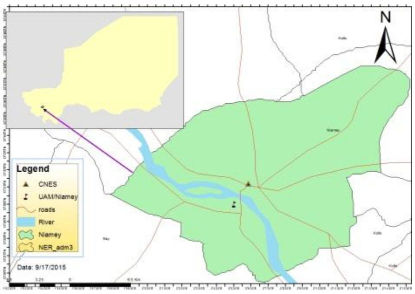

Figure 4: Map of the study area

Historical trend of temperature and global solar radiation over the area of study

Knowledge of solar potential for a particular area is needed for the solar PV technologies.
The figure below shows the variation of the temperature and the horizontal global radiation during the last thirty (30) years. The data used to make this graph is obtained from Nasa power agroclimatology (NASA) [11]. It is noticeable that the temperature trend is increasing over the area of study. This is an indicator that shows the warming event and hence the climate change. For the solar radiation, the trend is not uniform: it is observed a decrease in solar radiation from 1984 to 1999 and and an increase from 2000 to 2013.

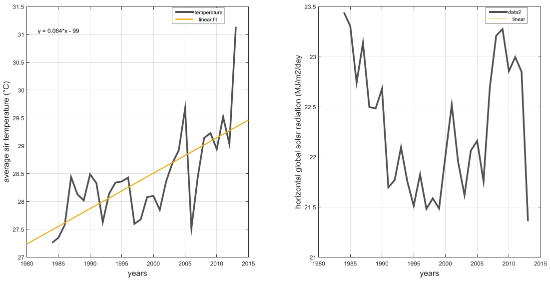

Figure 5: historical trend of ambient temperature and horizontal global solar radiation

Materials

For this study, a solar PV module of peak power equal to 100Wp has been used. The module containing twenty one monocrystalline solar cells of dimension 16*16 cm^2. A battery of 76 Ah is used. The other materials used are: charge regulator to monitor the state of the battery's charge and solar inverter. Two digital multimeters are used for the measurement of the current, voltage, and the ambient temperature. We also used data from the pyranometer with a datalogger installed in CNES to complete our dataset. This pyranometer provides horizontal global radiation, inclined (15°) global radiation and diffused radiation each five (5) minutes. The material used for the measurement of the PV output are presented in the figure. The characteristics of the solar panel used is summarized in the table 1 below.

Table 1 : Module characteristics provided by the manufacturer

Peak Power (Wp)	V_{OC} (V)	I_{SC} (A)	I_{MP}(A)	V_{MP}	η (%)
100	24	6.4	5.71	17.6	17.38

The figure 6 shows the various materials used to carry out this study.

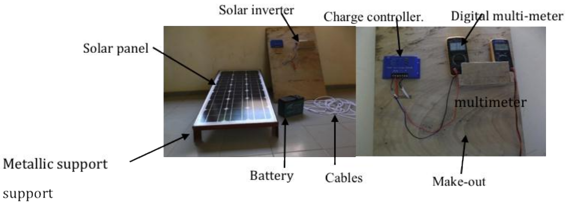

Figure 6 : materials used for the study

Measurement and data processing

- Photovoltaic output parameters

Maximum output current and voltage of the PV module are measured and recorded every day at interval of thirty minutes using a digital multi-meter for the months of April, May, June, and partly July and August. From these recorded values, daily average and monthly average values of maximum power are estimated using the following equation

$$P_{PV} = I * V, \qquad (2)$$

With P_{PV} the power output of the PV module, I is the output current, V is the output voltage.
Furthermore, the daily energy produced by the PV module from 7 AM to 6: 30 PM is estimated using the following equation :

$$E_d = \sum_{t=7:00}^{t=18:30} P(t) * 0.5 \qquad (3)$$

With P_{PV} the power output of the PV module, I is the output current, V is the output voltage.

Furthermore, the daily energy produced by the PV module from 7 AM to 6: 30 PM is estimated using the following equation:

$$E_d = \sum_{t=7:00}^{t=18:30} P(t) * 0.5 \qquad (4)$$

Where E_d is the daily energy produced by the PV module in Watt-hour/day, P (t) is the PV output power for a given time, 0.5 is the interval time in hour. From this result we easily estimated the daily PV output energy in watt-hour per square meter (Watt-hour/m^2/day) generated by this particular module and also the average daily energy for each month (from April to August) using the equation

$$\overline{E_d} = \frac{\sum_{i=1}^{i=n} E_{di}}{n} \qquad (5)$$

With $\overline{E_d}$, the average daily energy and n the number of days in the month.

Measurement *of temperature*

A digital multi-meter with a temperature sensor is used to measure the ambient temperature and the temperature of the cell for a few days in June in order to study the relationships between the ambient temperature and the PV cell temperature in one hand and between the ambient temperature and the PV power production in other hand. For that, the rotary switch is set at TEMP position and the key type thermoelectric couple is connected to “V” and “COM” jacks. The zero (initial value) is between 18 and 28°C according to the relative humidity of area. To get the real temperature we remove the initial value from the display temperature value in degree Celsius.

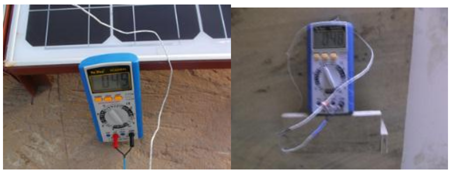

Figure 7: measurement of the ambient temperature around the module

Solar radiation and relative humidity data

The global solar irradiance measured at CNES (see the figure 8) has been used in this study

Figure 8: Pyranometer installed in CNES on a tilt angle of 15°.

Then the solar radiation received by the panel was estimated using the following equation

$$Prad = G * A_P \qquad (6)$$

Where P_{rad} the radiation received by the solar panel in Watt, G is the radiation impinging on the solar panel in W/m^2 and A_P is the area of the panel in m^2. And then, using the equation **3.3**, we also estimate the daily average energy received by the PV module.

The relative humidity data were obtained from NASA power agroclimatology website (NASA) [11].

Correlation coefficient

The correlation coefficient designed by the letter r is a coefficient that illustrates a quantitative measure of some correlation and dependence, meaning statistical relationships between two or more random variables or observed data values. In this study the Pearson's correlation coefficient given by the equation 7 will be used to quantify the statistical relationships between the PV output power and the different parameters such as temperature, relative humidity and conversion efficient $r = r_{px} = \frac{\sum_{i=1}^{n}(p_i - \bar{p})(x_i - \overline{x})}{\sqrt{\sum_{i=1}^{n}(p_i - \overline{p})^2} * \sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}}$ (7)

Where r is the correlation coefficient ranging from -1 to +1, p_i is the PV output power at a given instant, $\overline{p}$ is the average PV output power, $x_i \; and \; \bar{x}$ is the parameter and the average value of the parameter being correlated with the PV output power respectively.

If r is closer to zero (0), there is no correlation or the correlation is weak. A perfect correlation ± 1 occurs when all the data point lie on a straight line. If, r $= \pm 1$, the slope of this line is positive and we have a positive correlation. In contrast, if, r $= -1$ the slope of the line is negative and we have a negative correlation. For the values of r closer to one (1) the correlation is said to be strong.

4. Results & Discussion

4.1 Average power output of solar radiation and PV output power

The figure 9 shows the average daily irradiance and power output profiles for the months of April, May, June, July, and August. From this graph, it is observed that for the study area, all the months have the same pattern of variation. The maximum irradiance and output power are obtained along a wide spam of time. This result is of great importance in case when there will be a need to implement a hybrid system. For that one can rely on the electricity produced by the solar photovoltaic for a long time.

The maximum solar irradiance and output power are obtained in April whereas the minimum ones are in August. The lower values in August can be attributed to cloudiness conditions. Indeed, cloud cover reduces drastically the direct component of solar irradiance and hence weakens the incoming global solar radiation. Consequently, the power output of the PV module is also reduced, as light equals to power. So the more solar radiation the module receives the more output power is generated.

The table 2 gives the maximum, minimum, and average values of daily radiation and daily photovoltaic energy yield.

Months	**DailySolarEnergy (Wh/m^2/day)**			**Daily PV Energy (Wh/ Wh/m^2/day)**		
	Max	Min	Ave	Max	Min	Av
April	7004	5020	5809	1007	659	820
May	6385	4288	5610	939	506	710
June	6545	2876	5626	896	384	807
July	6803	3052	5120	887	497	713
Aug	6675	1033	5155	925	137	685

These extreme values are of great importance in case there is a need to implement a solar PV project

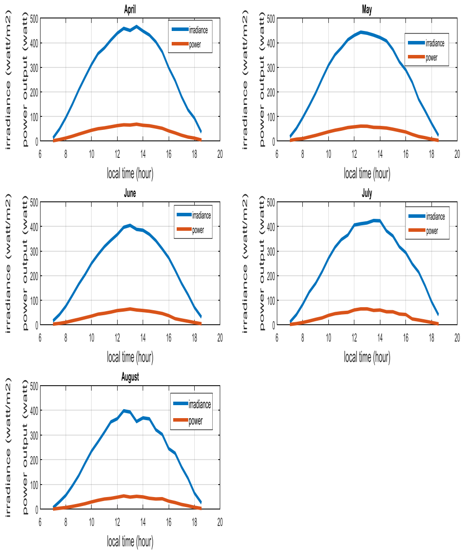

Figure 9: daily average profile of solar irradiance and module power output

4.2 Average daily profile of ambient temperature

The graphs of figure 10 show the average daily profile of ambient temperature around the solar panel over the area of study for the months April, May, June, July and August with the maximum values in May and June (Hot season) and minimum values in July and August (rainy season). However the month of April presents a profile that is slightly different from the other months: cold in the morning and a sharp increasing of ambient temperature by 9: 30 AM. This can be attributed to the fact that April is considered to be the transition month between the Harmattan that is known to be very cold in the morning over the study area and the hot season. Another observation is that the daily maximum temperature appeared in the afternoon – evening period. This fact is due to the lag between the peaks of irradiance and temperatures (Garcia & Balenzategui) [12]

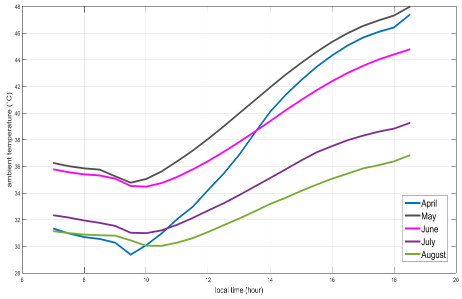

Figure 10: daily average profile of ambient temperature.

4.3 Effect of ambient temperature on the conversion efficiency of PV module

4.3.1 *Average variation of PV module efficiency*

The figure 11 shows the average daily profile of the conversion efficiency of the module over the study area from April to August. From the graphs of this figure it is observed that for all the months, the conversion efficiency is maximum around solar noon. A similar result has also been found by (Touati et al.) [13]. However the month of August presents many fluctuations due to regular occurrence of heavy clouds that reduce drastically the direct component of the global solar irradiance and hence the power output. In contrast, in April the profile of efficiency is more constant due to clear sky conditions. The maximum values of conversion efficiency are obtained in June and July due to low values of ambient temperature observed within these two months. In July a sharp decrease in efficiency is due to evening clouds that occur between 4 and 5 PM

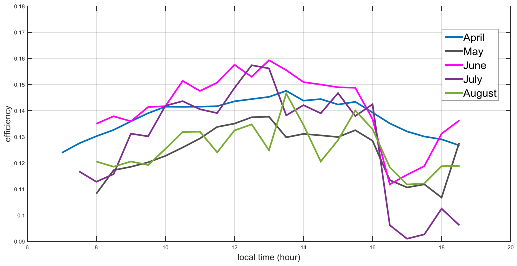

Figure 11: Average daily profile of conversion efficiency.

The table 3 gives the maximum, minimum, and average values of ambient temperature and the conversion efficiency for the months of April, May, June, July, and August

From the table 3, it's observed that the minimum values of conversion efficiency correspond to the maximum value of ambient temperature.

The correlation coefficients between the ambient temperature and conversion efficiency obtained are -0.53 for May and June, -0.28 and -0.20 for July and August respectively. These values show that the ambient temperature and the conversion efficiency are negatively correlated. The higher the ambient temperature is, the lower the conversion efficiency of the module.

4.3.2 Impact of temperature on PV electrical parameters

The ambient temperature has significant effect on short circuit current (I_{SC}), open circuit voltage (V_{OC}), output current (I) and output voltage (V). The output current and the short circuit current increase slightly whereas the open circuit voltage decreases with the ambient temperature. For the output voltage, it increases slightly up to a certain ambient temperature value and after it decreases drastically with the increase of the ambient temperature.

Table 3: average daily ambient temperature and conversion efficiency from April to August

Months	**Ambient temperature (˚C)**			**Conversion efficiency (%)**		
	Max	Min	Ave	Max	Min	Av
April	39.1	36.01	37.4	16.31	12.99	14.09
May	43.02	36.7	40.4	14.54	11.51	12.81
June	40.7	32.8	38.5	16.24	11.62	13.67
July	38.76	30.4	34.2	17.1	10.88	14.08
Aug	39.65	28.9	32.9	14.92	10.61	12.66

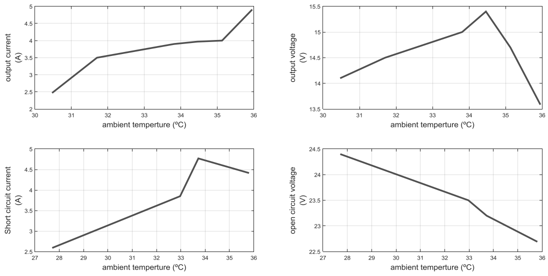

Figure_12: effects of ambient temperature on PV electrical parameters

4.3.3. ***Impact of ambient temperature on PV conversion efficiency and power output***

High temperature decreases the output power and the conversion efficiency of the module. Indeed the slope of the output power and the conversion efficiency are -2.6 W/ºC and -0.49/ ºC respectively. In other terms it means that the output power and the conversion efficiency decrease by 2.6 W and 0.49% respectively when the temperature increases by 1 ºC. The figure 13 shows the graph of the efficiency and output power against the temperature. From this graph it is clearly shown that the increase in ambient temperature has a negative impact on both the output power and the conversion efficiency. Indeed, when the temperature increases, the output voltage drops drastically with a slight increase in output current. So the overall power reduces and hence the efficiency of the module is low.

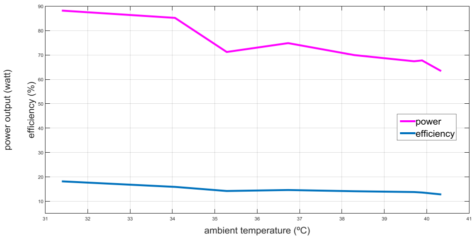

Figure 13 : effect of ambient temperature on power output and conversion efficiency

4.4 Impacts of relative humidity on the performance of PV modules

The graph below shows the effect of relative humidity on daily energy production. From this graph it is observed on average that the higher the relative humidity is, the lower the energy output. Indeed with an increase of one per cent (1%) of relative humidity induces a decrease of 4.3 Watt-hour/m^2 (Δenergy/Δ(RH) =-4.3watt-hour/m^2/1%RH). The month of April shows the lowest values of relative humidity therefore the highest daily energy output.

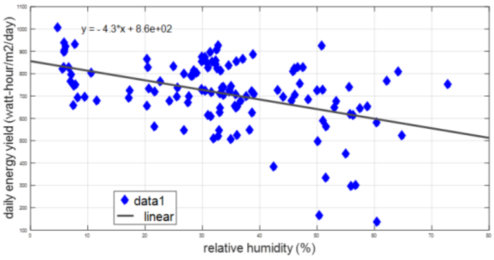

Figure 14 : relative humidity against daily energy output

4.5 Daily average variation of PV module energy yield

In order to classify the different months in terms of daily energy output it is important to know the average value of each month. The graph of the figure 14 shows the average daily energy production from April to August. From the graph it is clearly observed that the highest daily energy production on average is obtained in April (around 850 Wh/m^2/day) and the lowest in August (below 700 Wh/m^2/day). The lower values recorded in May and August are attributed to higher values of ambient temperature and lower values of solar irradiance respectively.

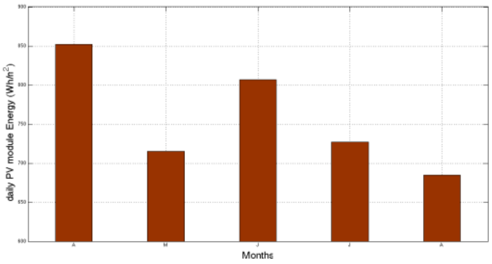

Figure 15: average daily energy production from May to August

4.6 Results and Discussion

The impact of ambient temperature on solar PV module has shown that for an increase of 1ºC, a decrease of 2.6 W of power output corresponding to 2.6%. Regarding to the module efficiency, an increase of 1ºC induced a decrease of 0.49%. However, in theory, a value of 0.4% reduction in power output for an increase of 1ºC has been found by (Radziemska) [14]. This difference between the obtained value and the theoretical value is mainly due to climatic conditions of the study area. Nevertheless, some similar works have been done throughout the world. The results show also the same decreasing trend of power output and efficiency with the increase of temperature (Bucher; Al-Sabounchi; Nishioka et al.) [4, 15, 16].

Regarding to the relative humidity, the results of this work has shown also a decrease in energy with increase of humidity. This can be attributed to the fact that during high relative humidity the atmosphere contains a wide range of water vapour particles sizes. So when light hits the water droplets, three scenarios may happen. It may be refracted, reflected, or diffracted. These effects plunge the reception level of the direct component of the solar irradiance impacting on the output power and on the daily energy output of the PV module. Similar results were found by (Fesharaki et al.; Touati et al.) [5, 13].

5. Conclusion

The effect of ambient temperature and relative humidity on the performance of monocrystalline solar module installed on the rooftop at Abdou Moumouni University of Niamey has been investigated. In addition, the daily energy output of the module was also estimated. Results show that the ambient temperature and the conversion efficiency are negatively correlated. Indeed, the slope of conversion efficiency and the ambient temperature was estimated to be -0.49%/˚C. So there is a need to improve the temperature coefficient for conversion efficiency in order to reduce the energy loss by temperature.

Also, the daily energy output and the relative humidity are negatively correlated. An increase of 1%RH causes a decrease of 4.3 Wh/m^2/day.

Moreover, the maximum energy yield is obtained in April (high solar radiation and moderate temperature) whereas the lower energy is obtained in May (high solar radiation and high ambient temperature) and August (low solar radiation, high relative humidity and low ambient temperature). So the high values of ambient temperature, high value of relative humidity and low values of solar irradiance are not favourable for the best performance of the module.

In this paper, a monocrystalline solar module has been used to investigate the effect of ambient temperature on the photovoltaic performance in Niamey. For the future work, it will be worthy to use many technologies of photovoltaic solar cells in order to know which technology is more suitable for the study area. Also performing the measurement for all the months of the year for both ambient temperature and photovoltaic output power will improve this work

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We would like also to dedicate this paper to the memory of Prof. ABDOULAYE Alassane the first Director of WASCAL Master Research Program on Climate Change and Energy of University Abdou Moumouni.

Nomenclature

CNES: National Centre of Solar Energy
CSP: Concentrating Solar Power
PV: Photovoltaic
PPV: Photovoltaic power output
IRENA: International Renewable Energy Agency.
NASA: National aeronautics and Space Administrations.
STC: Standard Test Conditions
UAM: Abdou Moumouni University
TC: Temperature of the cell
Iph: Photon current
Isat: Saturated current
ISC: Short circuit current
VOC: Open circuit voltage
RS: Series Resistance
AP: Area of the panel
G: Global inclined radiation
R: Correlation coefficient
M2: square meter
KW: kilowatt
KWh: kilowatt-hour
MW: Megawatt
GW: Gigawatt
eV: electron-volt
K : Boltzmann constant
Q : electron charge
˚: degree
˚C: degree Celsius

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