ANKARA YILDIRIM BEYAZIT UNIVERSITY

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PERFORMANCE ANALYSIS OF HYBRID PHOTOVOLTAIC-THERMOELECTRIC (PV/TE) SOLAR SYSTEMS

M.Sc. Thesis by

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M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"PERFORMANCE ANALYSIS OF HYBRID PHOTOVOLTAIC-THERMOELECTRIC (PV/TE) SOLAR SYSTEMS"** completed by **AICHATOU GALY ADAM** under the supervision of **DR. BULENT YEŞILATA** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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Date: June 05, 2020 **Aichatou Galy Adam**

PERFORMANCE ANALYSIS OF HYBRID PHOTOVOLTAIC-THERMOELECTRIC (PV/TE) SOLAR SYSTEMS

ABSTRACT

The improvement of the efficiency of the photovoltaic (PV) modules is the focus nowadays of so many researchers. Many test and research were conducted in order to reach that goal. That is how they came with the idea of a hybrid. Combining the PV module with the thermoelectric module is an innovative approach to improve the efficiency. Thus, not only a part of the solar spectral is exploited as for the PV alone, but a larger spectrum is exploited because the heat too is used. It allows the cooling of the panel and provide an additional power.

A comprehensive review on these previous research studies are presented here. Many methods and approaches to enhance the performance of the PV/TE systems are discussed along. The gaps in existing literature are identified and recommendations for future research are precisely outlined. It is emphasized here that only few experimental studies on PV/TE systems are exist. Therefore, it is highly recommended here that comprehensive experimental studies under real atmospheric conditions should be done with these systems.

Our work was based on a simulation of the efficiency of a tandem made of a PV panel and a TEG module. The simulation was done using the atmospheric conditions of Niger, which is a promising site for the exploitation of solar energy. The results obtained support the previous work and confirm the hypothesis that the addition of a TEG enhance the power output of the PV panel. It was shown that the Hybrid had a better efficiency than the PV stand alone. The lowest efficiency for the two modules were recorded at a cell temperature of 72.03 °C. The enhancement in efficiency of the hybrid is more noticeable at that point: the efficiency of the stand-alone PV is of 12.24% and the efficiency of the hybrid is slightly higher with a value of 19.62%.

Keywords: PV/TE efficiency, PV/TE hybrid, PV/TE efficiency improvement.

HİBRİT FOTOVOLTAİK-TERMOELEKTRİK (PV / TE) GÜNEŞ SİSTEMLERİNİN PERFORMANS ANALİZİ

ÖZ

Fotovoltaik (PV) modüllerin verimliliğinin iyileştirilmesi, günümüzde pek çok araştırmacının odak noktasıdır. Birçok fikirlerle birlikte bu amaca ulaşmak için birçok test ve araştırma yapılmıştır. PV modülünü termoelektrik modül ile birleştirmek verimliliği artırmak için yenilikçi bir yaklaşımdır. Bu nedenle, sadece güneş spektralinin bir kısmı PV için olduğu gibi değil, aynı zamanda ısı da kullanıldığı için daha büyük bir spektrumdan faydalanmaktadır. Panelin soğutulmasına izin verir ve ek güç sağlar.

Bu önceki araştırma çalışmaları hakkında kapsamlı bir inceleme burada sunulmuştur. PV/TE sistemlerinin performansını artırmak için birçok yöntem ve yaklaşım tartışılmaktadır. Mevcut literatürdeki boşluklar tanımlanmış ve gelecekteki araştırmalar için ciddi öneriler verilmiştir. Burada, PV/TE sistemleri üzerinde sadece birkaç deneysel çalışmanın mevcut olduğu vurgulanmaktadır. Bu nedenle, bu sistemler ile gerçek atmosfer koşullarında kapsamlı deneysel çalışmaların yapılması şiddetle tavsiye edilir.

Çalışmamız, bir PV panel ve bir termoelektrik jeneratör (TEG) modülünden oluşan art arda dizili verimliliğinin simülasyonuna dayanıyordu. Simülasyon, güneş enerjisinin kullanımı için umut verici bir yer olan Nijer'in atmosfer koşulları kullanılarak yapılmıştır. Elde edilen sonuçlar önceki çalışmayı desteklemekte ve bir TEG eklenmesinin PV panelinin güç çıkışını arttırdığı hipotezini teyit etmektedir. Hibrit'in tek başına PV'den (photovoltaik panel) daha iyi bir verime sahip olduğu gösterilmiştir. İki modül için en düşük verim, 72.03 ℃ hücre sıcaklığında kaydedilmiştir. Hibridin verimliliğindeki artış bu noktada daha belirgindir: bağımsız PV'nin verimi% 12,24'tür ve hibridin verimi% 19.62'lik bir değerle biraz daha yüksektir.

Anahtar Kelimeler: Fotovoltaik/Termoelektrik PV/TE verimi, PV/TE hibrid, PV/TE verim artışı.

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NOMENCLATURE

Roman Letter Symbols

a	Area
A	Diode ideality
E	Energy
FF	Fill Factor
G	Irradiance
h	Heat transfer coefficient
I	Current
I_0	Saturation current
J	Joule
K	Kelvin
k	Boltzman constant
$\overline{k}$	Total thermal conductance
k_i	Temperature coefficient
N_s	Number of pv cell in series
P	Power
q	Charge of electron
Q_{cs}	Heat flow cold side
Q_{hs}	Heat flow hot side
S	Seebeck coefficient
T	Temperature
V	voltage
V_t	Thermal voltage
R	Resistance
R_{te}	Electric resistance

Greek Letter Symbols

η	Efficiency
α	Seebeck coefficient

α_P	Seebeck coefficient P junction
α_N	Seebeck coefficient P junction

Subscripts

c	Cold
cs	Cold side
d	Diode
h	Hot
hs	Hot side
Hy	Hybrid
max	Maximum
non	Non absorbed radiation
oc	Open Circuit
ph	Photovoltaic
ref	Reference
s	Serie
sc	Short Circuit
sh	Shunt
T	Temperature

Acronyms

CPV	Concentrated Photovoltaic
DSSC	Dye Sensitized Solar Cell
HGS	hybrid generation system
HW	Hot Water
MJSC	Multi Junction Solar Cell
MPPT	Maximum Power Point Tracking
PCM	Phase Change Material
PTC	Parabolic Through solar Collector
PV	Photovoltaic
QD	Quantum Dot
QW	Quantum Well

SSA	Solar Selective Absorber
STC	Silicon Thin Cell
TE	Thermoelectric
TEG	Thermoelectric Generator
TEM	Thermoelectric module

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CHAPTER 1

INTRODUCTION

1.1 Main Framework

Our world is confronted to a very high emission of carbon dioxide which is creating big trouble to the environment. The overuse of minerals and fossil fuels is bringing them to a certain extinction. To solve this problem, the use of environmentally friendly and more available power sources is necessary. Those power sources are called renewable energy: solar, wind, biomass... The goal is to provide the world need in energy by using these sources. Solar energy has been more and more used, it is a very available source: we receive 4000 trillion kWh irradiation per day from the sun. solar energy can be enough to provide the daily need of the world in electricity.

A solar photovoltaic allow the conversion of sunrays to electricity with the use of semiconductors. When the semiconductor is irradiated by the sun and the photon energy is higher than the band gap energy of the solar cell, some holes-electrons are created. These electrons will be able to participate in the creation of electricity. This technology uses solar panels where solar cells are connected to form a module. An array is the connection of different modules in order to produce a certain level of power. The differences in the material uses in PV cells have a big role in the efficiency and applications. Nowadays, the efficiency of a common commercial solar panel alone is between 6 to -18%. The efficiency of a photovoltaic cell is given by the equation below:

$$\eta = \frac{P_{max}}{E.a_{cell}} \quad \textbf{(1.1)}$$

The light that illuminate the PV cannot be used all dues to some properties and default of the material used, some of the light is also reflected and not absorbed. The PV system can also become hot due to the illumination, that heat negatively affect its performance.

Photovoltaic system can be used as stand-alone application in some specialized applications. The PV covers 2% of the worldwide demand in electricity. It comes in third place as renewable energy in term of global capacity. The development of the technology makes it more affordable.

Thermoelectric is the use of heat to produce electricity. It uses the Seebeck effect. The differences of temperature on different place of a device create a voltage. The device can be made of two different metals same as semiconductors or even a combination of the two. Indeed, that difference is the origin of creation of electron-holes which will diffuse from high concentration to low concentration creating a thermally current. This module uses to generate electricity, as cooling system, or used as heat generator. The current generated can be continuous if the circuit is made of loop. The generated voltage can be calculated by:

$$V = \int_{T_1}^{T_2} 2\big(S_B(T) - S_A(T)\big)dT \qquad \textbf{(1.2)}$$

S_A and S_B are called Seebeck coefficients or thermopower of the metal A and B respectively.

The Seebeck coefficients give us the magnitude of the thermoelectric voltage induced by the differences in the temperature. Its unit is V/K.

If it is assumed that these thermopowers are constant according to the temperature range, the equation becomes:

$$\mathrm{V} = (\mathrm{S_B} - \mathrm{S_A}).(\mathrm{T_2} - \mathrm{T_1}) \qquad \textbf{(1.3)}$$

The electricity produced by a solar panel alone is reduced as the temperature goes higher. In order to correct this and maintain the solar cell at a reasonable temperature, many solutions have been discussed and tested in order to exploit that extra heat and produce more energy. It is in that dynamic that a Photovoltaic-Thermoelectric (PV/TE) idea was then brought up. A hybrid cell where the junctions of the thermoelectric modules are joint

with the one of photovoltaic. While a PV uses the UV of the solar spectrum and the thermoelectric uses the IR region, the combination of the two gives us a broader region. The hybrid module allows to cool down the photovoltaic modules and use the extra heat to create more power. Thus, this hybrid cell improves the efficiency of the photovoltaic cell. Its energy generation, power produced, and energy per unit area are higher than the one of the PV alone. Nevertheless, it is difficult to design and expensive to manufacture. It is said that the efficiency of the hybrid module will be able to reach and overpass an efficiency of 50.

Our work will focus on the theoretical part of the hybrid. We will simulate and see how the addition of a thermoelectric generator affect the efficiency and performance of the PV. We will check which results the hybrid will provide on a theoretical scale. We will perform these experiments using data from Niger. We believed no such work were done in our country and we would make to present some bases for the future researchers. We have a very vast territory that could be exploited to provide the country in electricity. It could be the solution to the lack of the country in electricity.

Indeed, Niger present a good potential when it comes to solar energy harvesting. Niger happens to be one of the hottest countries in the world. The temperature varies from 26 ℃ to 46 ℃ in average (see Fig.1.1). Nevertheless, the temperature can reach and sometimes pass 50 ℃.

The country has a very good irradiation and its numbers of hours of irradiance is significant, reaching 9 hours in 2019 (see Fig. 1.4). The irradiance varies from 5.1 kWh/m^2 to 6.3 kWh/m^2 as was stated by Maigargue D. et al. [1] in their paper titled “Evaluation of the solar potential in Niger” through the years 2015 and 2016.

The annual average Direct Normal Irradiance (DNI) of the country varies from 1534 kWh/m^2 to 2556 kWh/m^2, decreasing from North to South while the Global Horizontal Irradiance (GHI) increase from the South to the North, with an average annual range between 2118 to 2410 kWh/m^2 (see Fig. 1.2 & Fig. 1.3).

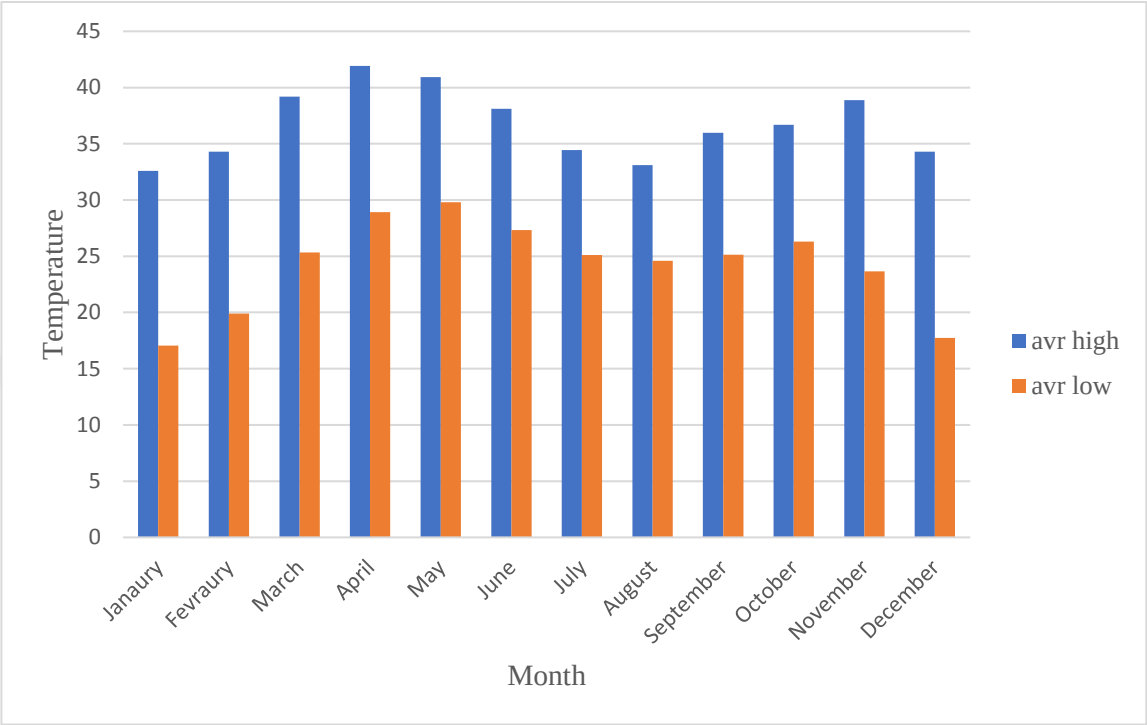

Figure 1.1 Average temperatures in Niamey capital city of Niger in 2019

The daily PV power output in Niger varies between 4.6 kWh/kWp to 5.6 kWh/kWp. The highest annual PV power potential is recorded in the north and has a value of 2045 kWh/kWp.

Presenting an average of 6 kWh/m^2 irradiance per day, with an annual need of 465 GWh in electricity, by exploiting 1.4 km^2 of PV panels, the country can become electrically independent (Fig.1.5). It would be completely possible to fulfill this need taking in account that the country presents a lot of unoccupied space. The Sahara Desert could be exploited in order to implement a PV central.

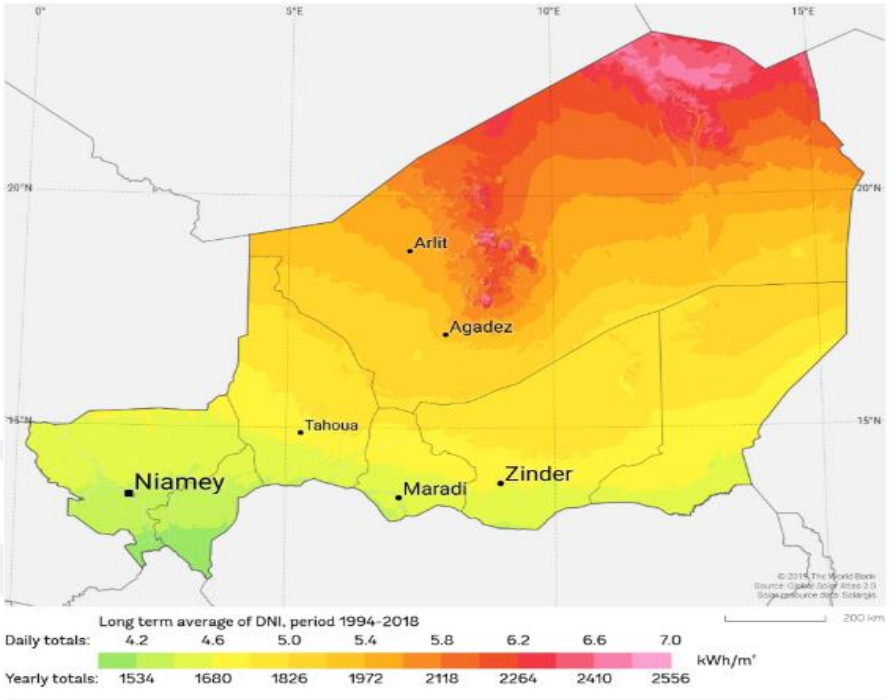

Figure 1.2 Distribution of direct normal irradiance in Niger [2].

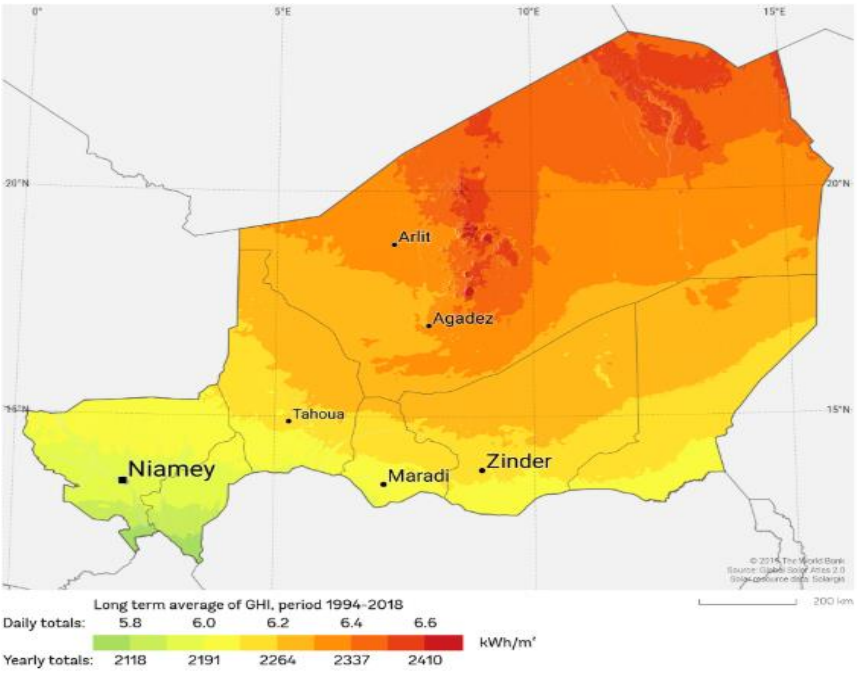

Figure 1.3 Distribution of global horizontal irradiance (GHI) in Niger [2].

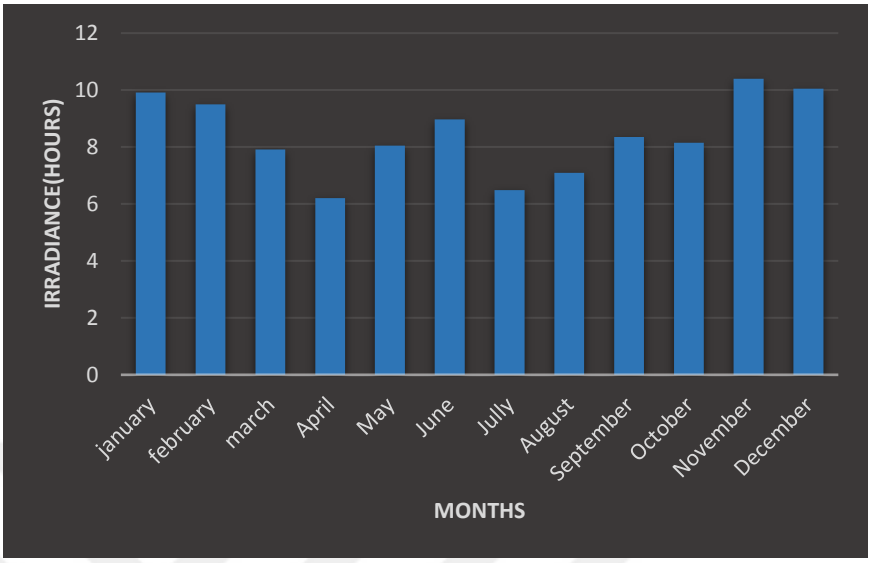

Figure 1.4 Average hours of irradiance in Niamey city in 2019

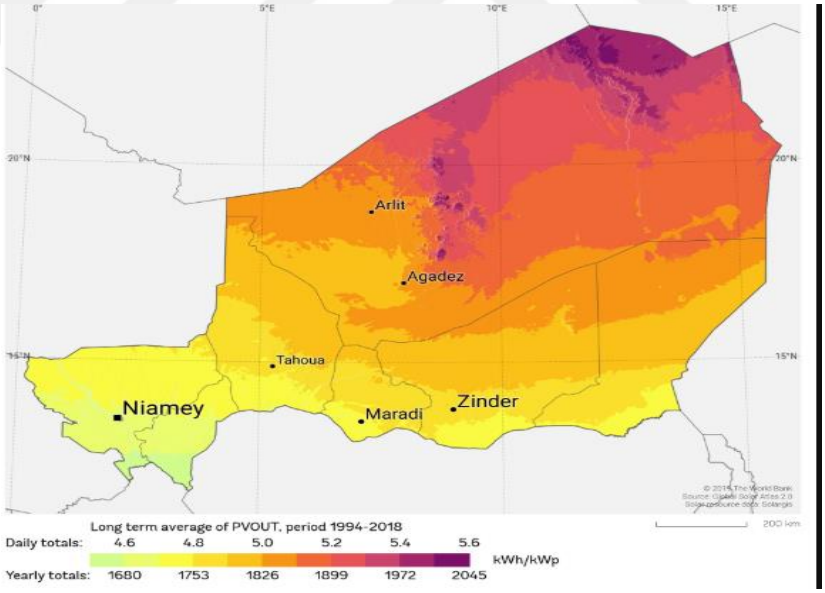

Figure 1.5 PV power potential in Niger [2].

1.2 Hybrid PV/TE Mechanism

The hybrid cell is composed of a photovoltaic cell which has at its the back a module made of two contacts (see Fig. 1.6). These two contacts form a thermoelectric generator. One

of the contacts is connected directly to the back of the photovoltaic cell to collect the extra heat. The second contact is in contact with the ambient air. It is where the Seebeck effect takes effect. The difference of temperature between the two plates creates a voltage which can be added to the electricity generation of the photovoltaic system.

Thus, the solar photovoltaic module made of semiconductors convert the sunrays into electricity, by the system of creation of the electron-holes and their transport. While doing so the PV module happens to heat up and this decrease it efficiency. That is when the thermoelectric generator become useful.

Indeed, the thermoelectric generator will use that temperature difference to create electricity by the via of the Seebeck effect. Thus, extra energy is produced, which will be a bonus to add to the output power produced by the PV module.

During the modelling of the hybrid, the different modules are taken separately then the results added up. This approach does not really put in evidence that the use of the extra heat, by the thermoelectric generator, allows the PV cell not to overheat and to work under better condition thus, allow to increase its efficiency.

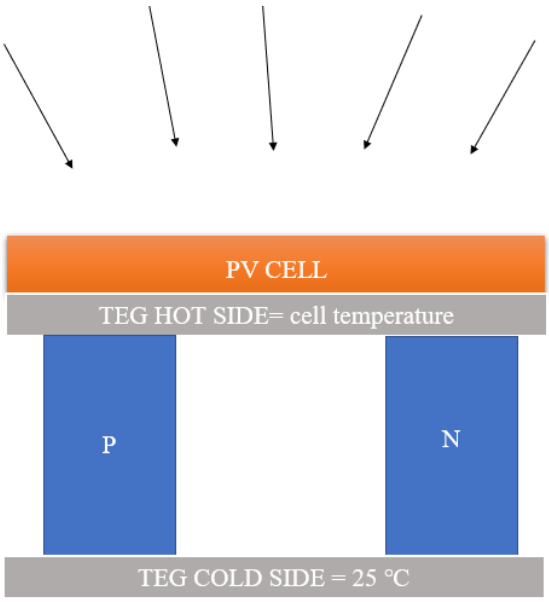

Figure 1.6 Simple PV/TEG design

CHAPTER 2

PREVIOUS WORK

A proceedings paper[1] written by A. G. Adam and B. Yeşilata [3], who are respectively the writer and the advisor of this thesis, was published as an early output of this thesis work. The paper consisted on the discussion of previous work made on the PV/TE hybrid. The brief highlights of the most relevant work are summarized in **Tale 2.1**.

Table 2.1 A brief highlights of the most relevant work on PV/TE systems

Ref.#	Authors (years)	Material /System	Method /Application	Summary of results
[4]	Wang et al. (2011)	DSSC/TEG /SSA	Experimental	Produce high conversion efficiency, the efficiency went from 9.39% to 13.8%
[5]	Zhang (2014)	Concentrating PV/TE	Theoretical	Test were conducted using different PV cells. The thin silicone film and copper indium gallium selenide cell are promising.
[6]	Li et al. (2016)	PV/TE	Simulation	It was noticed that the overall efficiency was linear to the efficiency of the TEG. efficiency improve with increasing cross section area

[1] Adam, A. G., & YEŞİLATA, B. (2019, October). Use of Hybrid Photovoltaic-Thermoelectric (PV-TE) solar module for Enhancing Overall System Efficiency. In *2019 3rd International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)* (pp. 1-8). IEEE.

Table 2.1 (continued) A brief highlights of the most relevant work on PV/TE systems

[7]	Beeri et al. (2015)	PV/TE	Experimental	The concentration is the origin of increase in the efficiency. A 32% was reached. In the future they are expecting a 50% efficiency
[8]	Cui et al. (2016)	PV/TE/PCM	Theoretical	The use of PCM is to control the change of temperature in the hybrid. Many PV cells were investigated. A better efficiency was found with the hybrid compare to stand alone.
[9]	Dallan et al. (2015)	PV/TE	Experimental	Increased of power output up to 39% once the thermal parameters are fixed
[10]	Ying et al. (2015)	Glazed PV/TE vs unglazed PV-TE systems with nanofluid heat sink	Theoretical	Nanofluid lead to an increase in the efficiency
[11]	Deng et al. (2013)	PV/TE and heat collector	Numerical-Simulation	The hybrid made of STC gave A power output three times higher than the power output of stand alone

Table 2.1 (continued) A brief highlights of the most relevant work on PV/TE systems

[12]	Lin et al. (2015)	PV/TEG	Theoretical	Use of a TEG composed of multi-couples thermo elements gave a better performance than the stand-alone PV or stand-alone TEG.
[13]	Kil et al. (2017)	PV/TEG	Experimental	Single junction gallium arsenide and TEG hybrid gave an efficiency 3% higher
[14]	Pang et al. (2015)	PV/TEG	Empirical study	The addition of TEG to the PV cell allow an improvement of 27% in the efficiency
[15]	Yang et al. (2011)	PV/TEG/HW	Theoretical-Experimental	The addition of TEG and heat exchanger for hot water increase the total efficiency which is 30% higher than the efficiency of PV/TEG or PV/HW
[16]	Soltani et al. (2017)	PV/TE with nanofluids	Experimental	SiO_2/water nanofluid gave a power 54,29% higher while the efficiency goes higher by 3.13%
[17]	Zhu et al. (2016)	PV/TE	Theoretical-Numerical	A 23 % efficiency was observed during an experiment conducted outside. The TEG was the origin of production of an extra 648 J without sunlight

Table 2.1 (continued) A brief highlights of the most relevant work on PV/TE systems

[18]	Kwan et al. (2016)	PV/TE	Experimental	The utilization of a single stage TEG is preferable to optimize the overall efficiency of the hybrid.
[19]	Kossyvakis et al. (2016)	PV/TE	Experimental -Theoretical	Two hybrids made of two different solar cells were investigated, a poly-Si cell and a DSSC. The efficiency of the DSCC hybrid is 30.2% while the poly-Si is of 22.5%
[20]	Verma et al. (2016)	PV/TE	SIMULINK /MATLAB	They concluded that the hybrid presents a better efficiency and also it can be implemented under any climatic conditions and anywhere.
[21]	Soltani et al. (2018)	PV/TEG-PTC	MATLAB	A 22.714 W was achieved with G=998 W/m^2

CHAPTER 3

MATHEMATICAL MODELING AND SIMULATION

3.1 Mathematical Modeling of a PV Cell

3.1.1 Ideal Single Diode

The simplest way to represent a PV cell is to use diode. It is the most understandable circuit. The electrical equivalent circuit of a PC cell is represented as follow:

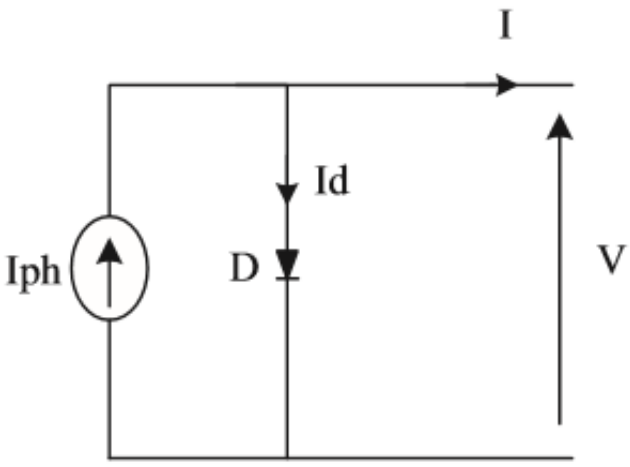

Figure 3.1 Electrical model of a solar cell

For this circuit, three important parameters need to be found. These are the short circuit current (I_{sc}), the open circuit voltage (V_{oc}) and the ideality factor (A).

The current ***I*** is given by the relation:

$$I = I_{ph} - I_d \tag{3.1}$$

where $\boldsymbol{I_{ph}}$ is the photo-current generated by the PV cell at 25 ℃ with 1000 W/m^2 and $\boldsymbol{I_d}$ the diode current. The diode current is given by the following equation:

$$I_d = I_0\ (e^{\frac{V}{A\,V_t}} - 1) \quad \textbf{(3.2)}$$

where A is the diode ideality, V_t is the thermal voltage and I_0 is the dark saturation current.

The thermal voltage can be written according to N_s, the number of cells in series

$$V_t = \frac{N_s k T}{q} \quad \textbf{(3.3)}$$

where $q\ is$ the electron charge, T the temperature of the cell and k the Boltzman constant which is equal to $1.38\ 10^{-23}\ J/K$.

Replacing the equation (5) with the equation (4):

$$I = I_{ph} - I_0\ (e^{\frac{V}{V_t}} - 1) \quad \textbf{(3.4)}$$

The short circuit current I_{sc} is found when the voltage $V = 0$

$$I_{sc} = I_{ph}|_{V=0} \quad \textbf{(3.5)}$$

The open circuit voltage V_{oc} is found by making $I = 0$ A. Thus, the equation **3.4** becomes

$$I_{ph} = I_0\ (e^{\frac{V_{oc}}{V_t}} - 1) \quad \textbf{(3.6)}$$

$$\ln(\frac{I_{ph}}{I_0} + 1) = \frac{V_{oc}}{V_t} \quad \textbf{(3.7)}$$

$$V_{oc} = \frac{1}{V_t}\ \ln(\frac{I_{ph}}{I_0} + 1) \quad \textbf{(3.8)}$$

At the Maximum Power Point (MPP) we can find the maximum voltage and the maximum current. The maximum current will be given by replacing the voltage in the diode equation:

$$I_{max} = I_{ph} - I_0 \left(e^{\frac{qV_{max}}{AN_S kT}} - 1\right) \quad \textbf{(3.9)}$$

where N_s is the number of PV cell connected in series in the photovoltaic panel.

The derivative of the maximum current equation (**3.9**) according to V_{max} we get the Maximum voltage equation:

$$V_{max} = \frac{AN_S kT}{q} \ln\left(-\frac{AN_S kT}{qI_0}\left(\frac{dI}{dV}\right)_{V_{max}}\right) \quad \textbf{(3.10)}$$

Let us assume:

$$\frac{dI}{dV}\Big|_{V_{max}} \cong -\frac{0 - I_{sc}}{V_{oc} - 0} = -\frac{I_{sc}}{V_{oc}} \quad \textbf{(3.11)}$$

thus, the maximum voltage and current are equal to:

$$V_{max} = \frac{AN_S kT}{q} \ln\left(\frac{AN_S kT}{qI_0}\,\frac{I_{sc}}{V_{oc}}\right) \quad \textbf{(3.12)}$$

$$I_{max} = I_{ph} + I_0 - \frac{AN_S kT}{q}\left(\frac{I_{sc}}{V_{oc}}\right) \quad \textbf{(3.13)}$$

The power is found by:

$$P = I_{sc}.V_{oc} \quad \textbf{(3.14)}$$

To find the maximum power we use the formula:

$$P_{max} = I_{max}.V_{max} \quad \textbf{(3.15)}$$

The fill factor can be calculated by:

$$FF = \frac{I_{max}.V_{max}}{I_{sc}.V_{oc}} \quad \textbf{(3.16)}$$

The efficiency is given:

$$\eta = P_{max}/P_{in} \quad \textbf{(3.17)}$$

Which can be written in order of FF:

$$\eta = FF.V_{oc}.I_{sc}/P_{in} \quad \textbf{(3.18)}$$

3.1.2 Actual solar panel circuit

The above case represented an ideal solar cell without losses. Actual solar panel do have some losses. To represent those loses it is more common to use the following circuit which has a shunt and a series resistance. Therefore, with the additions of these resistances, three more parameters need to be found. Using the paper release by Cubas et al. [22] we get the necessary equations for our work.

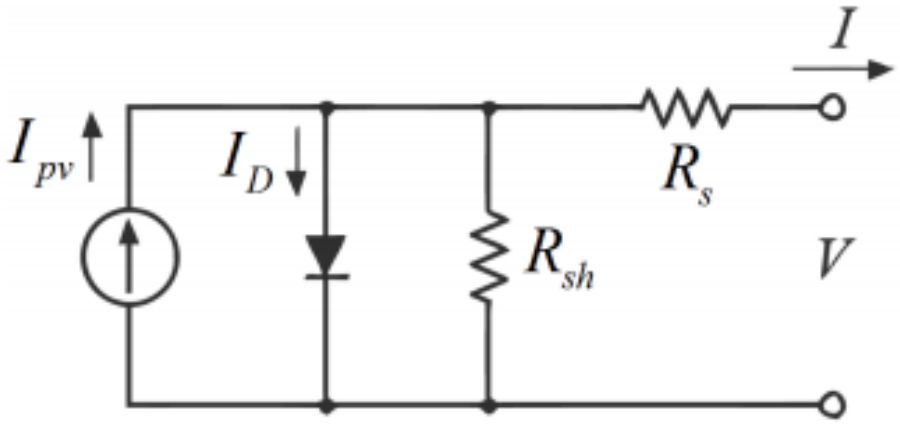

Figure 3.2. Actual PV panel representation with loses [22].

The current equation therefore becomes:

$$I = I_{pv} - I_0\left[\left(e^{\frac{V+IR_S}{AV_t}} - 1\right)\right] - \frac{V+IR_S}{R_{sh}} \quad \textbf{(3.19)}$$

where I_{pv} is the photocurrent , R_s is the series resistance and R_{sh} the shunt resistance. The thermal voltage can be written introducing the number of cells in series N_s.

$$V_t = \frac{N_s k T}{q} \quad \textbf{(3.20)}$$

Available PV datasheets give us information about three important point of the panel: the short circuit, open circuit, and maximum power point. By including theses data to the equation **(3.19)** , we can obtain three different equations.

At the short circuit point, by taking in account $I = I_{sc}$ and $V = 0$, we obtain:

$$I_{sc} = I_{pv} - I_0 \left[\left(e^{\frac{I_{sc} R_s}{A V_t}} - 1 \right) \right] - \frac{I_{sc} R_s}{R_{sh}} \quad \textbf{(3.21)}$$

At the open circuit point, taking in account the condition $I = 0$ and $V = V_{oc}$ we get

$$0 = I_{pv} - I_0 \left[\left(e^{\frac{V_{oc}}{A V_t}} - 1 \right) \right] - \frac{V_{oc}}{R_{sh}} \quad \textbf{(3.22)}$$

At the maximum power point, $I = I_{max}$ and $V = V_{max}$:

$$I_{max} = I_{pv} - I_0 \left[\left(e^{\frac{V_{max} + I_{max} R_s}{A V_t}} - 1 \right) \right] - \frac{V_{max} + I_{max} R_s}{R_{sh}} \quad \textbf{(3.23)}$$

If we take the derivative for power at the maximum points we get

$$-\frac{I_{max}}{V_{max}} = -\frac{I_o}{A V_t} . \left(1 - \frac{I_{max}}{V_{max}} R_s \right) . \left(e^{\frac{V_{max} + I_{max} R_s}{A V_t}} \right) - \frac{1}{R_{sh}} \left(1 - \frac{I_{max}}{V_{max}} R_s \right) \quad \textbf{(3.24)}$$

The four previous equations allow us to calculate the following parameters:

- The series resistance will be given by:

$$\frac{A.V_t.V_{max}(2I_{max}-I_{sc})}{[V_{max}.I_{sc}+V_{oc}.(I_{max}-I_{sc})].(V_{max}-I_{max}.R_s)-AV_t([V_{max}.I_{sc}-V_{oc}.I_{max})} = e^{\frac{V_{max}+I_{max}R_s-V_{oc}}{AV_t}} \quad \textbf{(3.25)}$$

- The shunt resistance is :

$$R_{sh} = \frac{(V_{max}-I_{max}.R_s)[V_{max}-R_s(I_{sc}-I_{max})-A.V_t]}{(V_{max}-I_{max}.R_s)(I_{sc}-I_{max})-A.V_t.I_{max}} \quad \textbf{(3.26)}$$

The saturation current is given by :

$$I_0 = I_{0,ref}.(\frac{T}{T_{ref}})^3.e^{\frac{q.E_{g0}.(\frac{1}{T_{ref}}-\frac{1}{T})}{A.k}} \quad \textbf{(3.27)}$$

Where

$$I_{0,ref} = \frac{I_{sc}}{e^{\frac{V_{oc}}{AV_t}}-1} \quad \textbf{(3.28)}$$

The photo current equation is given by:

$$I_{pv} = \left[I_0 + k_i.\left(T - T_{ref}\right)\right].\frac{G}{G_{ref}} \quad \textbf{(3.29)}$$

The value of A will be estimated for commodity.

An expression of the cell temperature using the ambient temperature and T_{noct} is given as follow:

$$T_{cell} = T_a + \frac{T_{noct} - 20}{800}G \quad \textbf{(3.30)}$$

3.2 Mathematical Modeling of a Thermoelectric Generator

The PV/TE is composed of a PV cell and a thermoelectric generator. We saw the modelling of the PV cell, let us look at the thermoelectric generator.

A thermoelectric generator is composed of many thermocouples. A thermocouple is the basic unit of a TEG. It is usually made of a P-type and N-type semiconductor. They are relied by a metal and they happen to be electrically in series and thermally in parallel. A thermocouple possesses two side, a hot and a cold one. That is how electricity is generated because of the thermal diffusion of carriers.

Using the Seebeck equation we got the basic equation

$$V = S(T_{hs} - T_{cs}) \quad \textbf{(3.31)}$$

Where

$$S = S_P - S_N \quad \textbf{(3.32)}$$

The heat flux on the two different side of a thermocouple are given by the equations:

$$Q_{hs} = S.I.T_{hs} + \bar{k}.(T_{hs} - T_{cs}) - \frac{1}{2}R_{te}.I^2 \quad \textbf{(3.33)}$$

$$Q_{cs} = S.I.T_{cs} + \overline{K}.(T_{hs} - T_{cs}) + \frac{1}{2}R_{te}.I^2 \quad \textbf{(3.34)}$$

with

$$I = \frac{S.(T_{hs} - T_{cs})}{R_{te} + R_L} \quad \textbf{(3.35)}$$

where R_L is the load resistance.

Thus, for a thermoelectric generator composed of n thermocouples the equations (**3.33**) and (**3.34**) become

$$Q_{hs} = n * (S\,.I.T_{hs} + \overline{K}.(T_{hs} - T_{cs}) - \frac{1}{2}R_{te}.I^2) \quad \textbf{(3.36)}$$

$$Q_{cs} = n * (S.I.T_{cs} + \overline{K}\,.(T_{hs} - T_{cs}) + \frac{1}{2}R_{te}.I^2 \quad \textbf{(3.37)}$$

The power generated by the thermoelectric generator is given by

$$P_{TEG} = Q_{hs} - Q_{cs} \quad \textbf{(3.38)}$$

$$P_{TEG} = n(S.I.(\,T_{hs} - T_{cs}) - R_{te}.I^2) \quad \textbf{(3.39)}$$

And its efficiency is found using

$$\eta_{TEG} = P_{TEG}/Q_{hs} \quad \textbf{(3.40)}$$

3.3 Mathematical Modelling of a PV/TEG

Dealing with the equations cited below, both for the photovoltaic system or the thermoelectric generator system, can be challenging. We have many unknows that make the simulation of these equations a bit difficult. Recalling that the basic hybrid is composed of a thermoelectric generator mounted directly to the PV system. Thus, we can assume that the temperature of the hot side of the thermoelectric generator is the temperature of the cell. In order to notice the change provided by adding the thermoelectric generator, we need to have the efficiency and power output with respect to the temperature for the PV alone and the tandem PV/TEG.

Kossyvakis et al [19] came up with equations allowing us to get the desired values.

To calculate the temperature of the PV device, they used the following equations:

$$T_{PV} = T_a + c.G \quad \textbf{(3.41)}$$

$$c = \frac{T_{noct} - 20}{800} \quad \textbf{(3.42)}$$

where T_a represents the ambient temperature, G the sun irradiance and C is a parameter depending of the installation and which is found according to the faculty of the PV cell to exchange heat with the environment.

The efficiency of the device with respect to the irradiance can hence be found by:

$$\eta_{PV} = \eta_{PVref}.[\,1 - \beta.(T_{PV} - T_{ref})] \quad \textbf{(3.43)}$$

where β represents the temperature efficicency coefficient, η_{PVref} the reference efficiency of the device at the STC(standard test conditions), T_{ref}) the reference temperature which is normally 25℃.

The power output of the PV device is given by:

$$P_{PV} = \eta_{PV}.G.A \quad \textbf{(3.44)}$$

where A represents the area of the cell which is receiving the irradiation.

For the thermoelectric part, the team gave theses describing equations. They recalled that because the TEG is a heat engine, its conversion is limited by the Carnot efficiency.

$$\eta_{TEG,max} = \frac{T_{hs} - T_{cs}}{T_{hs}} . \frac{\sqrt{1+Z.\bar{\bar{T}}} - 1}{\sqrt{1+Z.\bar{\bar{T}}} + \frac{T_{cs}}{T_{hs}}} \quad \textbf{(3.45)}$$

where the Carnot efficiency is given by $\frac{T_{hs} - T_{cs}}{T_{hs}}$ and $\bar{T}$ is the absolute operating temperature and Z is the figure of merit of the TEG and:

$$\bar{T} = \frac{T_{hs} + T_{cs}}{2} \quad \textbf{(3.46)}$$

$$Z = S^2 \frac{\sigma}{k} \quad \textbf{(3.47)}$$

where σ is the electrical conductivity of the TEG and k its thermal conductivity

The output power is given by the equations (**3.38**) and (**3.39**), lets recall them:

$$P_{TEG} = Q_{hs} - Q_{cs} \quad \textbf{(3.38)}$$

$$P_{TEG} = n(S.I.(T_{hs} - T_{cs}) - R_{te}.I^2) \quad \textbf{(3.39)}$$

with □h □ and □□□ where Q_{hs} and Q_{cs} are given in equation (**3.36**) and (**3.37**) lets recall them, and the also the current equation given by equation (**3.35**)

$$Q_{hs} = n(S.I.T_{hs} + \overline{K}.(T_{hs} - T_{cs}) - \frac{1}{2}R_{te}.I^2) \quad \textbf{(3.36)}$$

$$Q_{cs} = n(S.I.T_{cs} + \overline{K}.(T_{hs} - T_{cs}) + \frac{1}{2}R_{te}.I^2 \quad \textbf{(3.37)}$$

$$I = \frac{S.(T_{hs} - T_{cs})}{R_{te} + R_L} \quad \textbf{(3.35)}$$

R_{te} for a pair of thermoelements is given by:

$$R_{te} = \frac{\rho_{e,p}.L_p}{A_p} + \frac{\rho_{e,n}.L_n}{A_n} \quad \textbf{(3.48)}$$

with L and A representing the length and the area of either the P or N element.

To get the maximum power output of the TEG, the load and internal resistance should be matched. So, we will assume that R_{te} and R_e have the same value.

The efficiency is then:

$$\eta_{TEG} = \frac{P_{TEG}}{Q_{hs}} \quad \textbf{(3.49)}$$

Thus, to have the power of the tandem we use the equation:

$$P_{HY} = P_{PV} + P_{TEG} \quad \textbf{(3.50)}$$

And the efficiency of the tandem is given by

$$\eta_{HY} = \frac{P_{HY}}{G.A} \quad \textbf{(3.51)}$$

$$\eta_{HY} = \eta_{TEG} + \eta_{PV} \quad \textbf{(3.52)}$$

3.4 Simulation

For our simulation we will use the simplest design of a PV/TEG hybrid (Fig. 3.8) using the following PV cell and TEG module whose data are in Table 3.1 and Table 3.2 . We also collected some data in term of the outdoor temperature in Niger. We will conduct our simulation based on data collected on a chosen date which is 7th May 2019 which appears to present very good irradiance and temperature.

Table 3.1 Specification of the TEG (Bi_2Te_3)

size	$40 * 40\ mm^2$
Number of couples thermoelement	128
Thermoelement cross section(W * D)	$1{,}4 * 1{,}4\ mm^2$
Maximum temperature	320 C
L_{TE} (length of thermoelement) (mm)	1,6
S $(^{\mu V}/_{K})$	282
$\overline{K}$	1.20 W/(m·K)
Number of TEG used in series	615

By using the data given by the manufacturers, H.R. Fallah Kohan et. al [23] were able to define the total internal resistance as follow:

$$R_{te}(total) = 10^{-5}.(-3)(\frac{T_{hs}+T_{cs}}{2}\text{-}273)^2\text{-}0.0133(\frac{T_{hs}+T_{cs}}{2}\text{-}273)$$

$$+1{,}54 \quad \textbf{(3.53)}$$

Which give us the internal resistance per thermoelements as follow:

$$R_{te} = R_{te}(total)/n \quad \textbf{(3.54)}$$

Table 3.2 Specification of the PV panel

Size	1480mm*665mm*35mm
Maximum power (P_{max})	150W
Optimum operating voltage (V_{mp})	17.2V
Optimum operating current(I_{mp})	8.72A
Open-circuit voltage(V_{oc})	21.6V
Short-circuit current(I_{sc})	9.92A
Isc temperature coefficient	(0.065 ±0.015)%/℃
Voc temperature coefficient	-(80 ±10)mV/℃
Peak power temperature coefficient	-(0.5 ±0.05)%/℃
NOCT(Air20℃;Sun 0.8kW wind 1m/s)	47±2℃
Operating temperature	-40℃to 85℃
Maximum system Voltage	1000V DC
Cell	Mono-crystalline Silicon Solar cells
No. Of cell and connection	36
Weight	13kg

CHAPTER 4

RESULTS AND DISCUSSION

The Fig. 4.1, Fig. 4.2, and Fig. 4.3, represent the temperature and the irradiance received in Niamey. The temperature values and irradiance were received from the Niamey Meteorology Center. Nevertheless the specific irradiance of 7th May was approximated using the daily average irradiance data received and the study of Maigargue D. et al. [1]. For January and September, the daily average values were used.

The Fig. 4.1 represents the daily temperature average of January 2019 in Niamey. The temperature goes from 15.13 ℃ to a maximum value of 30.66 ℃ recorded at 16:00. The irradiance varies from a value of 0 W/m^2 at 7:00 Am to a maximum of 1073.86 W/m^2 at 13:00 then start to decrease.

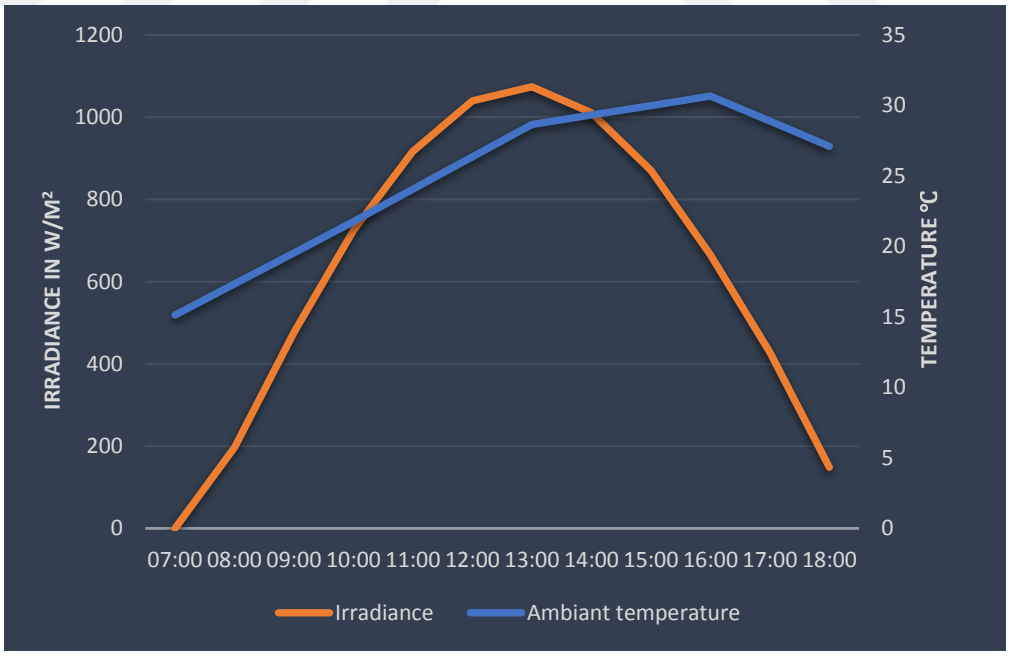

Figure 4.1 Averages temperature and irradiance curves of January 2019 in Niamey

The 7th May day was used because it has the highest temperature recorded in the year. The irradiance goes up to 970W/m^2 at 13:00 Pm and then start to go down. The irradiance was available from 6:00 Am and becomes 0 W/m^2 at 7:00 Pm. The temperature keeps rising during the day and reached the highest point at 17:00 Pm. From that time the temperature curve starts to decrease (see Fig. 4.2).

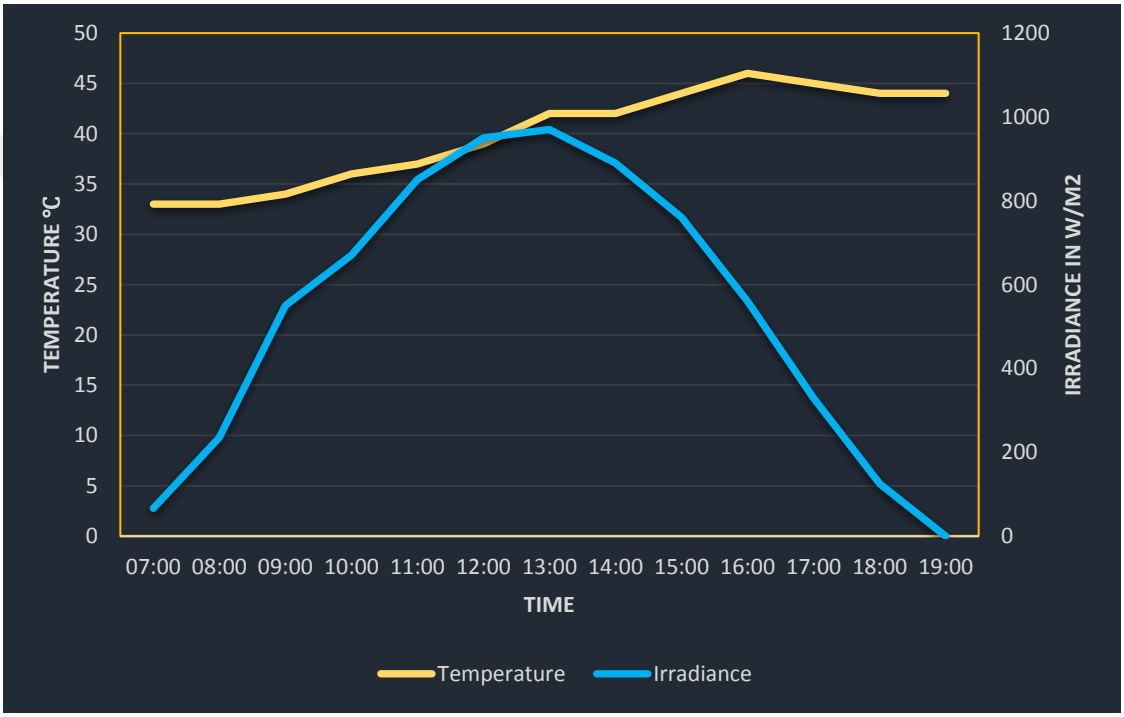

Figure 4.2 Temperature and irradiance curves of 7th May 2019 in Niamey

The Fig. 4.3 represents the daily temperature average of September 2019 in Niamey. The temperature goes from 25.57 ℃ to a maximum value of 35.04 ℃ recorded at 16:00. The irradiance varies from a value of 31.97 W/m^2 at 7:00 Am to a maximum of 856.25 W/m^2 at 13:00 then start to decrease.

From these values we can see that the amount of irradiance received between these three chosen months is greater in January, then comes September and finally the 7th May.

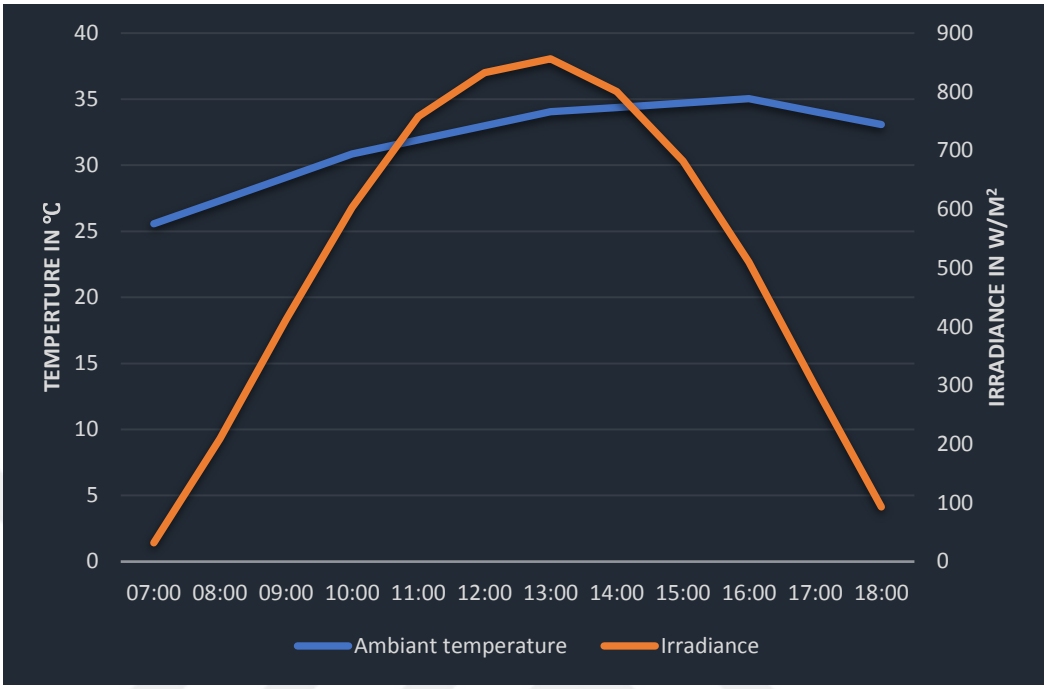

Figure 4.3 Average temperature and irradiance curves of September 2019 in Niamey

It is known that the irradiance affects the short circuit current. The cell temperature mostly affects the Voc. Indeed, at G= 550 W/m^2, the cell temperature is of the value of 51.56 ℃ with an I_{sc}=5.45 A and V_{oc}= 16.5 V (see Fig. 4.4). At G=950 W/m^2, the cell temperature is of 71.73 ℃ with a I_{sc}=9.42 A and v_{oc}=14.9 v (see figure 4.5). These results show the relation between irradiance, cell temperature and the resulting short circuit current and open circuit voltage values.

PV panel temperature and irradiance also influence the power output of the PV panel. These are shown by the Fig. 4.6 and Fig. 4.7. Indeed, the power increases as the irradiance goes higher. It can clearly be seen that the power has an undeniable rise from its value at G= 550 W/m^2 where v= 13.5 V and P=64.9W to its value when G=950 W/m^2 WHERE V=14.5 V and P= 95.69 W.

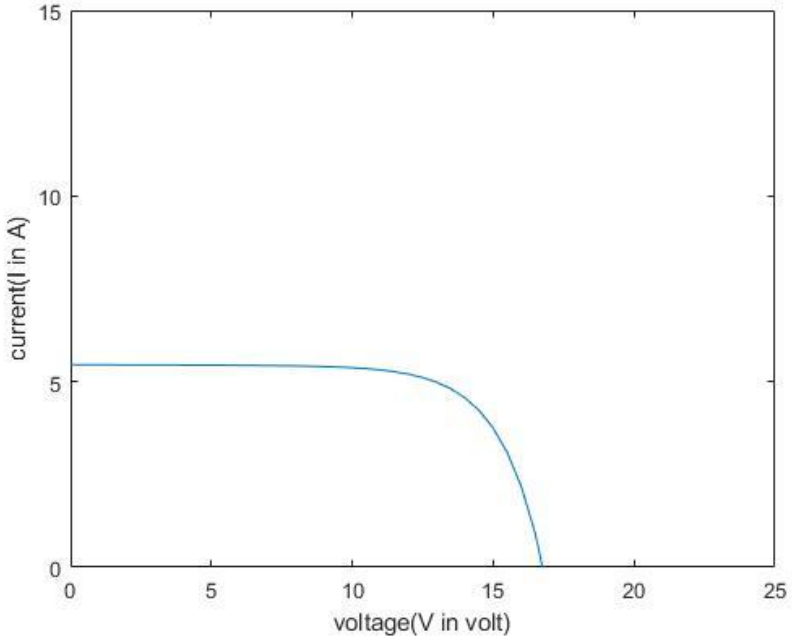

Figure 4.4 PV I/V curve at G= 550 W/m2 on 7th May

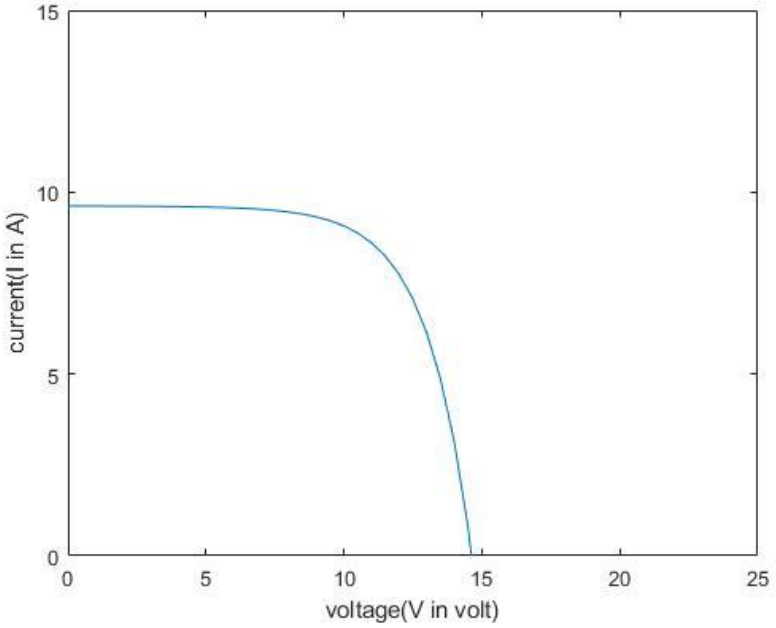

Figure 4.5 PV panel I/V curve at G= 950 W/m2 on 7th May

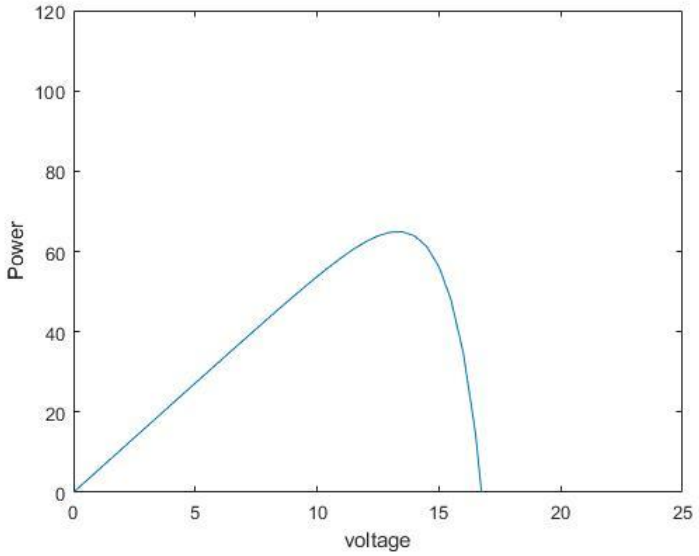

Figure 4.6 PV panel P/V curve at G= 550 W/m^2 on 7th May

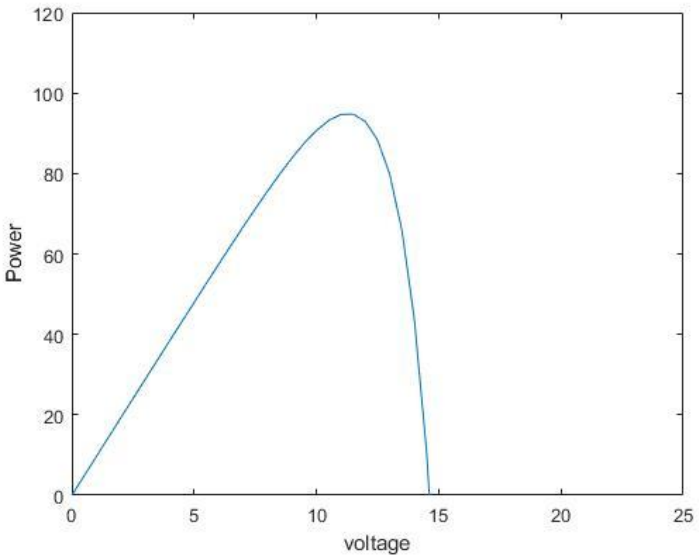

Figure 4.7 PV panel P/V curve at G= 950 W/m^2 on the 7th May

Let us recall that the cell temperature affects badly the power output of any PV cell, thus its efficiency. It was by the way in that goal that different ways of reducing that temperature were investigated as seen in our literature review. The results of our simulations made in January, 7th May and September show us that the higher the cell temperature the less efficient the PV panel is.

The same effect of temperature has observed during the simulations made on January and September (see Fig. 4.8, Fig. 4.9, and Fig. 4.10): as soon as the temperatures rises, the efficiency of the PV panel decreases, and then when the temperature start to go down the efficiency rise up. Indeed, as the temperature goes high, the efficiency goes down from 15.18 % to 12.24 % from the simulation made on 7th May (see Fig. 4.9). From that point the temperature of the cell starts decreasing thus the efficiency starts rising.

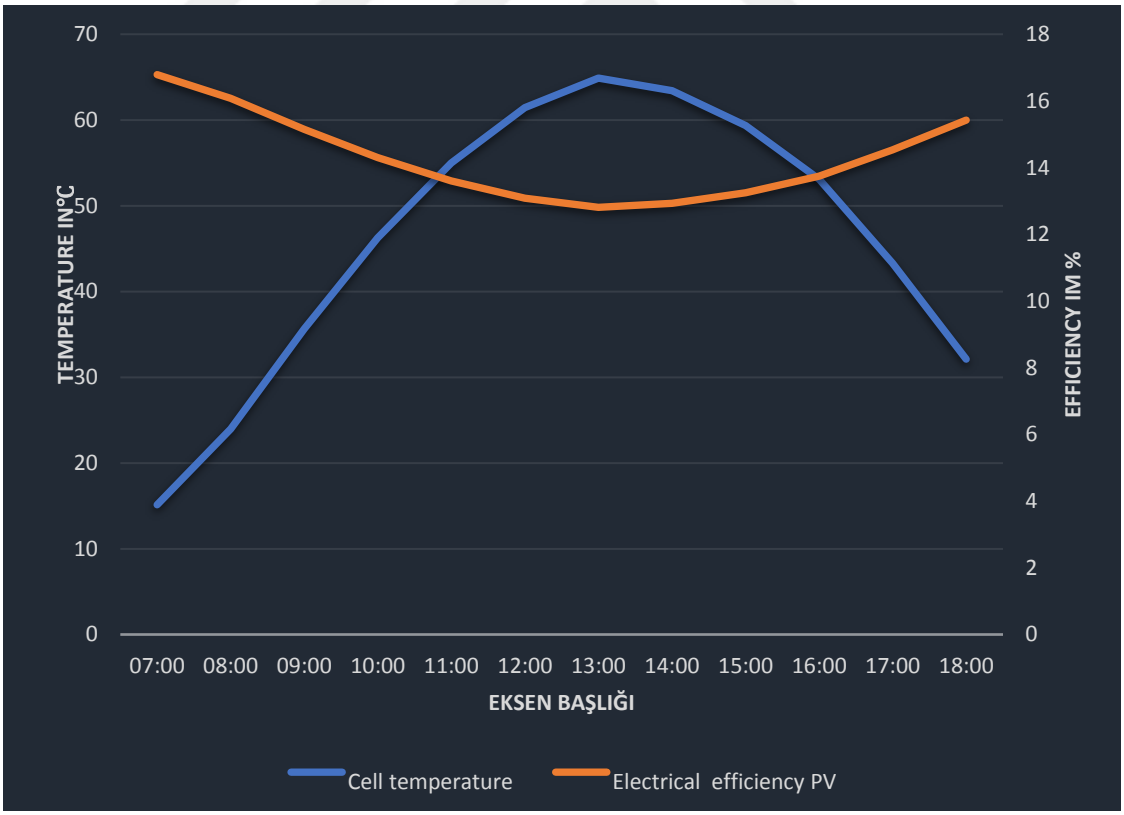

Figure 4.8 Effect of cell temperature on the PV panel efficiency on January 2019

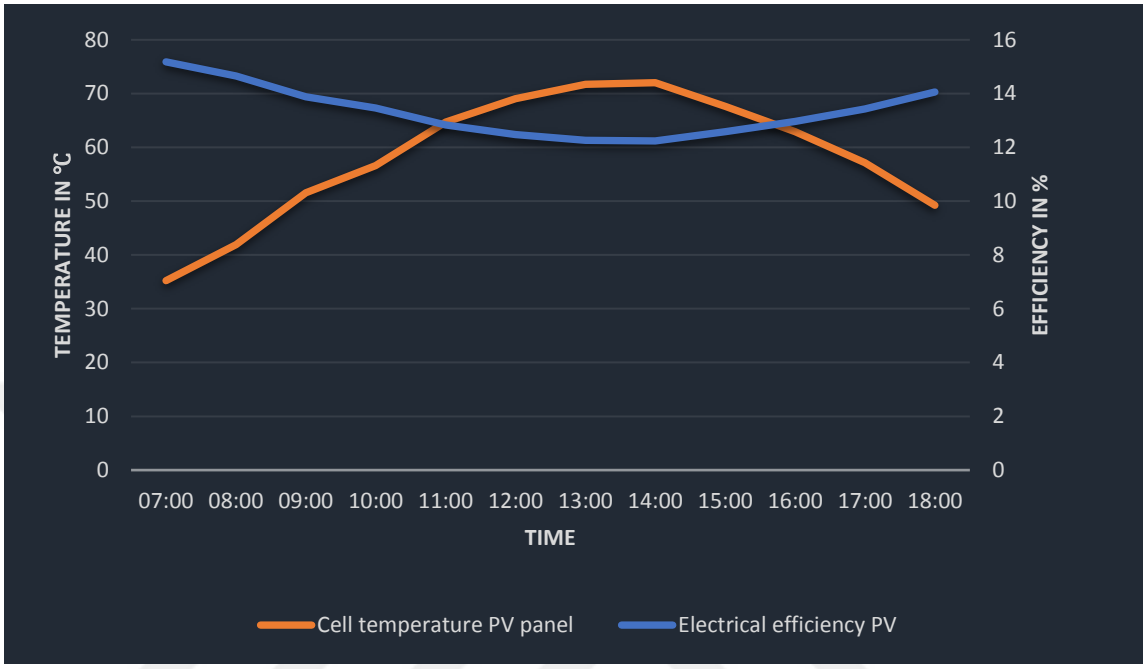

Figure 4.9 Effect of cell temperature on the PV panel efficiency on 7th May 2019

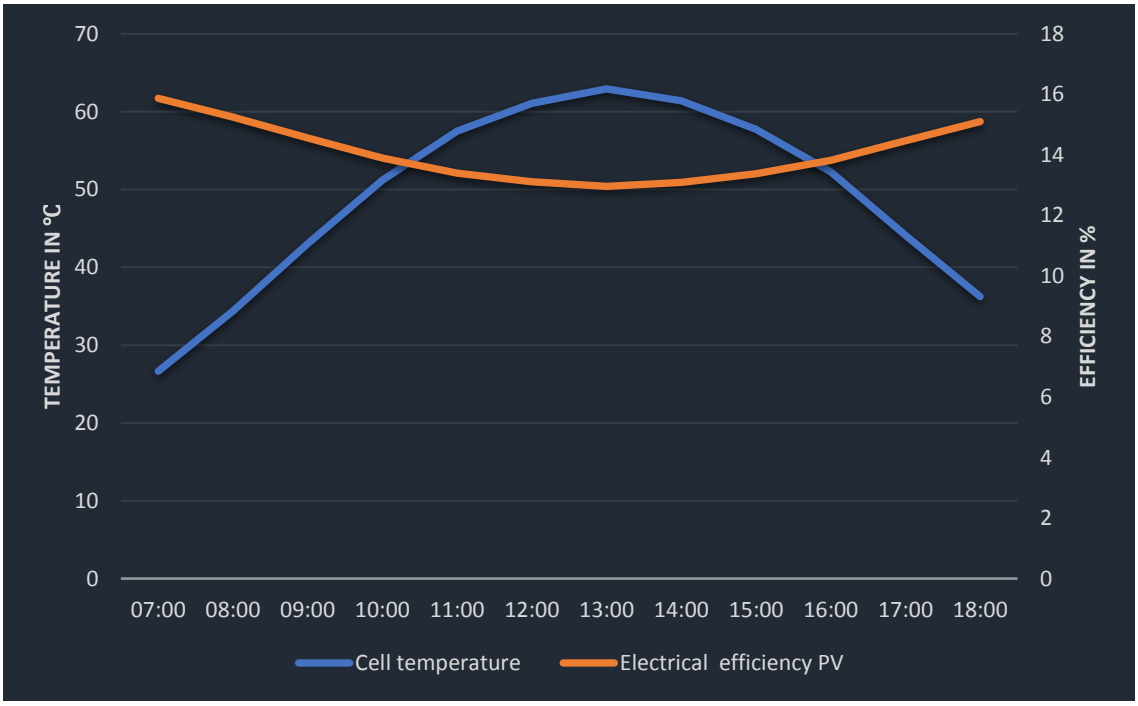

Figure 4.10 Effect of cell temperature on the PV panel efficiency on September 2019

On the other side, the higher the temperature difference between the two plates of the TEG, the higher the output power gets, thus its efficiency. With a cold side fixed at 25℃, and the cell temperature equal to the hot side of the TEG, it was logical that the higher the PV panel temperature get, the better the TEG efficiency becomes. The 7th May presented the highest efficiency as shown in Fig. 4.12. An efficiency of 7.31% was recorded at panel temperature equal to 72.03 ℃ while the lowest efficiency was recorded at a PV panel temperature of 35.22℃ and has a value of 1.19% .

The months of January and September gave a concordant result as it can be seen in Fig. 4.11 and Fig. 4.13.

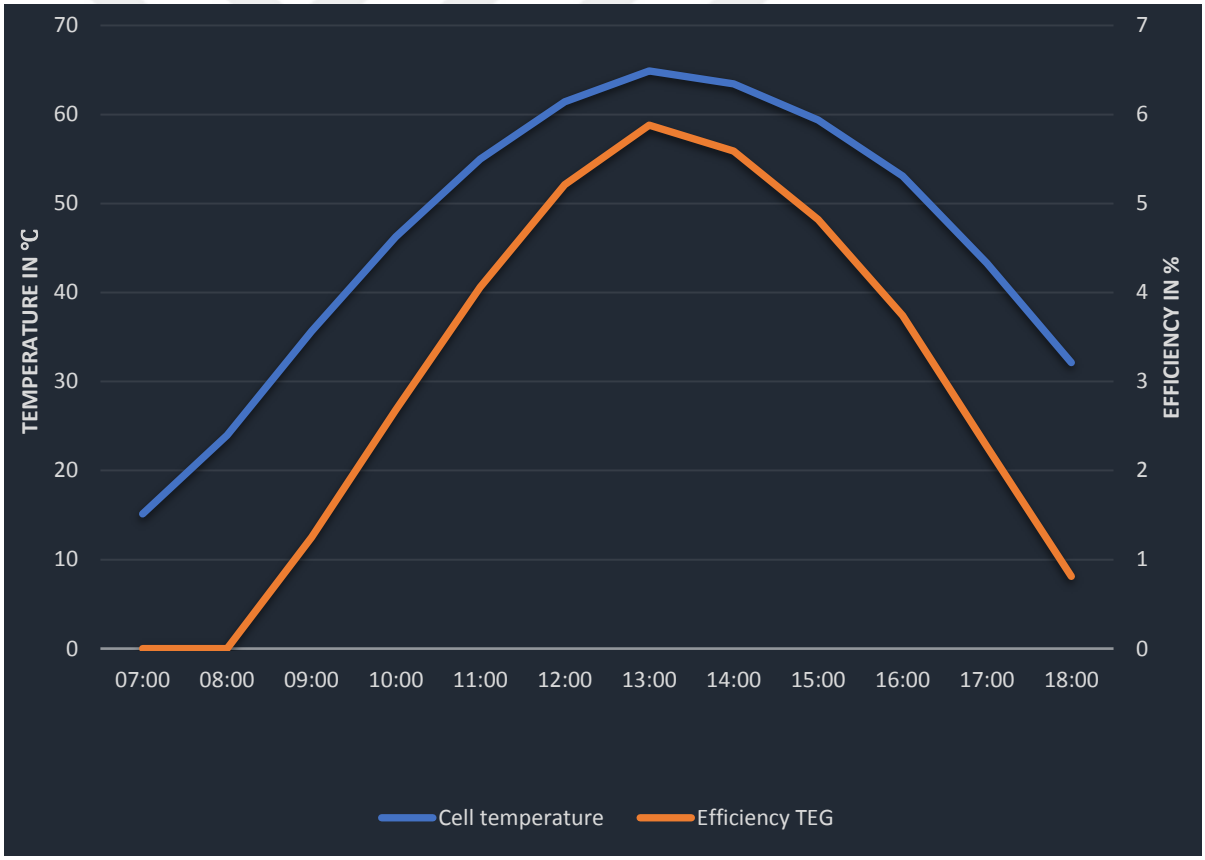

Figure 4.11 Influence of the PV panel temperature to the average TEG efficiency on January 2019

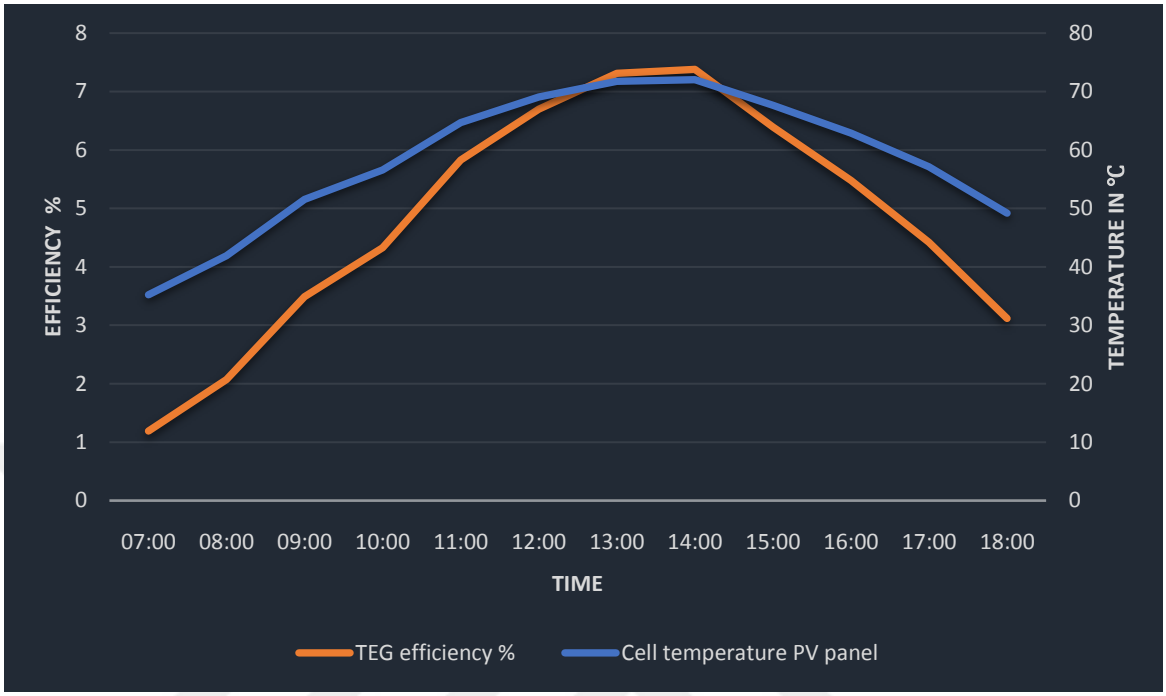

Figure 4.12 Influence of the PV panel temperature to the TEG efficiency on 7th May 2019

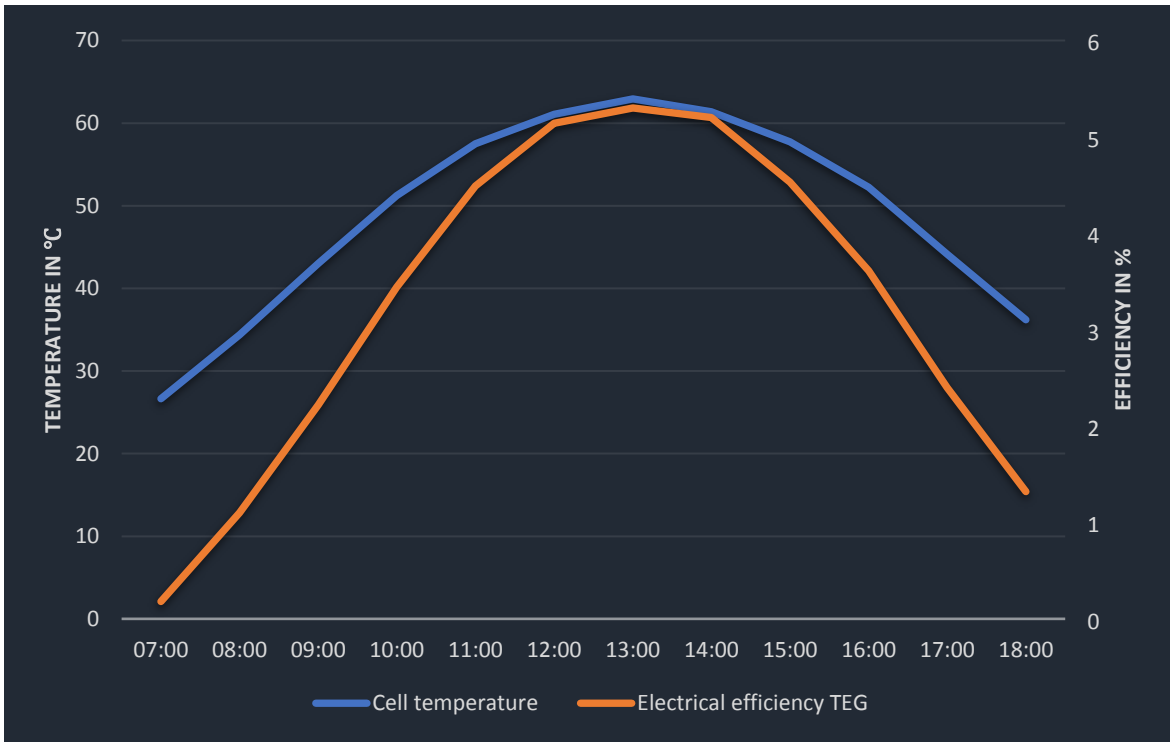

Figure 4.13 Influence of the PV panel temperature to the TEG efficiency on September 2019

There is a tradeoff happening in the total power production of the hybrid. Indeed, the cell temperature is a bad factor for the efficiency of the PV module but represents the biggest actor in the power production of the hybrid.

During the simulation in January 2019, the maximum power output of the stand-alone is of a value of 134.79 W while at the same point the hybrid had a 196.69 W power production (see Fig. 4.14). On the 7th May, the highest values of power were recorded at 13.00 Pm with 117.13 w and 186.91 W respectively for the PV alone and the hybrid (see Fig. 4.15). In September, the maximum power production is of 153.22 W for the hybrid while the stand alone exhibits a power production of 108.79 under the same conditions (see Fig. 4.16).

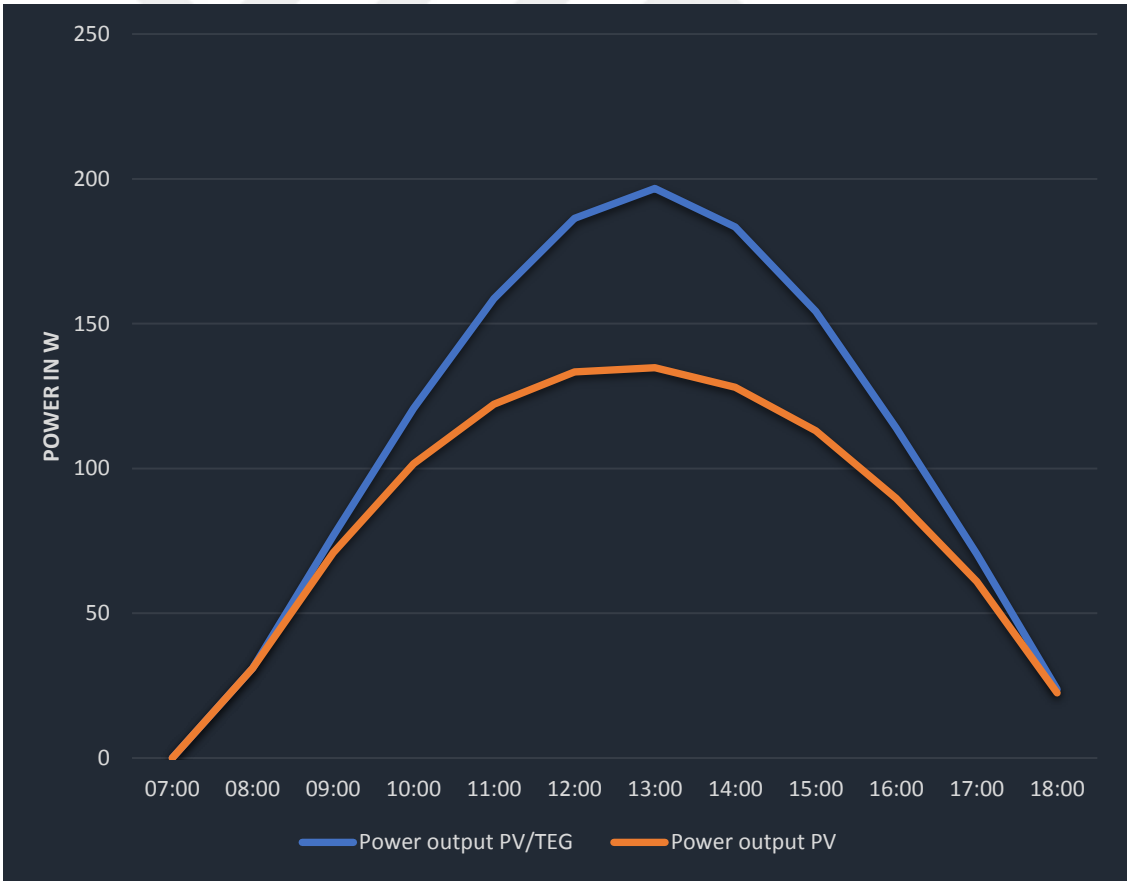

Figure 4.14 Power output for PV panel and PV/TEG on January 2019

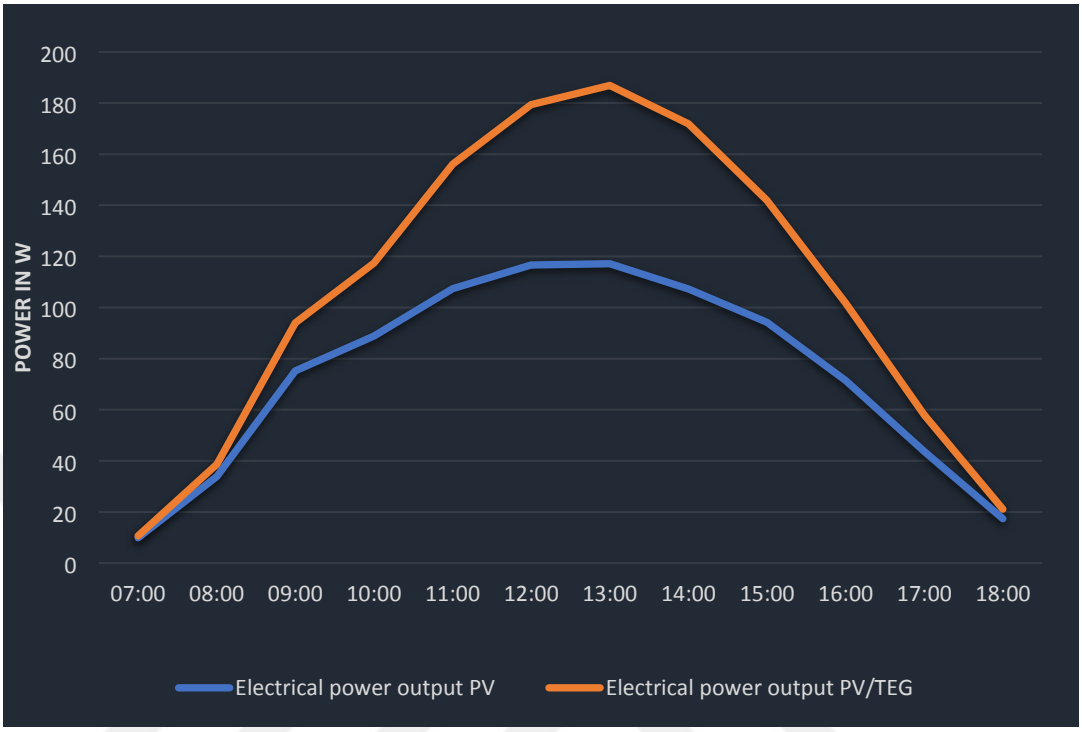

Figure 4.15 Power output for PV panel and PV/TEG on 7th May 2019

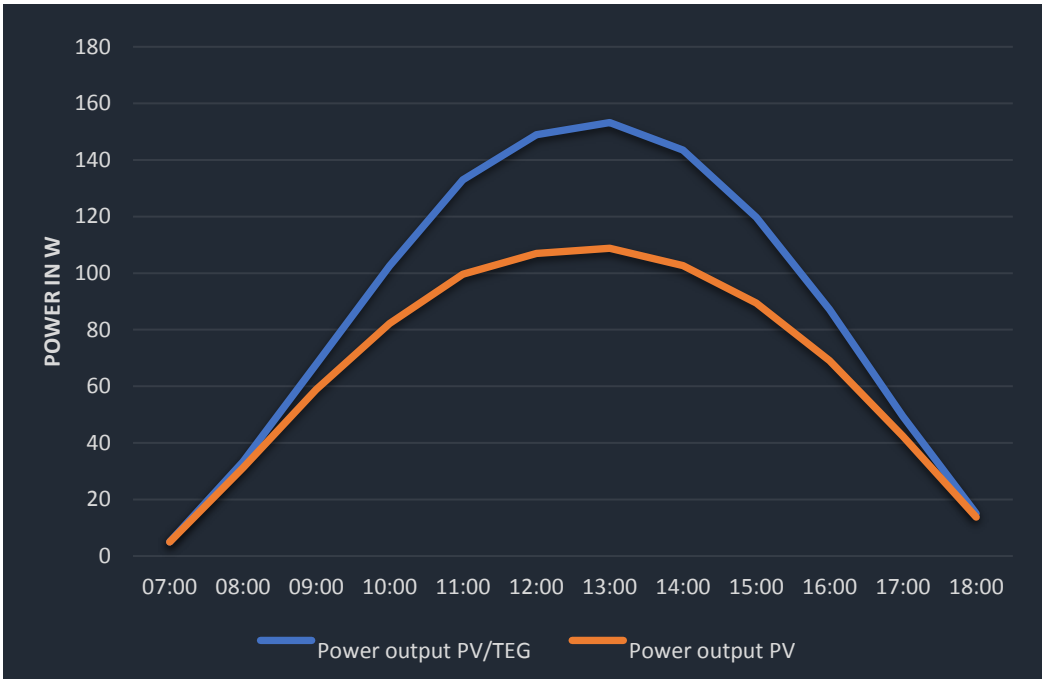

Figure 4.16 Power output for PV panel and PV/TEG on September 2019

Even though the apport in efficiency of the TEG does not exceed 7.38%, it was demonstrated that its addition to the PV panel is a good way to increase the overall efficiency of the hybrid.

These results come to confirm the hypothesis that the use of a PV panel and a TEG to form a hybrid is a good way of improving the power production of the PV panel. This work come to support the results published in all the work reviewed above in the literature section but also some more in the domain of PV panel efficiency enhancing. The efficiency improvement is more obvious for the hybrid as the temperature goes higher. The difference between the two efficiencies gets greater as the cell temperature increases. At 13:00 PM, the efficiency of the stand-alone PV panel is at its lowest due to the increase in the temperature, while it can be clearly seen that the hybrid's efficiency is at its highest. the results obtain during the simulation conducted on 7th May 2019 the results were more obvious than the ones conducted on January or September. At a cell temperature of 72.03℃, which is the highest cell temperature of the day, the efficiency of the PV panel alone is of 12.26 % , whereas at the same point the Hybrid presents an efficiency of 19.57% (see Fig. 4.18).

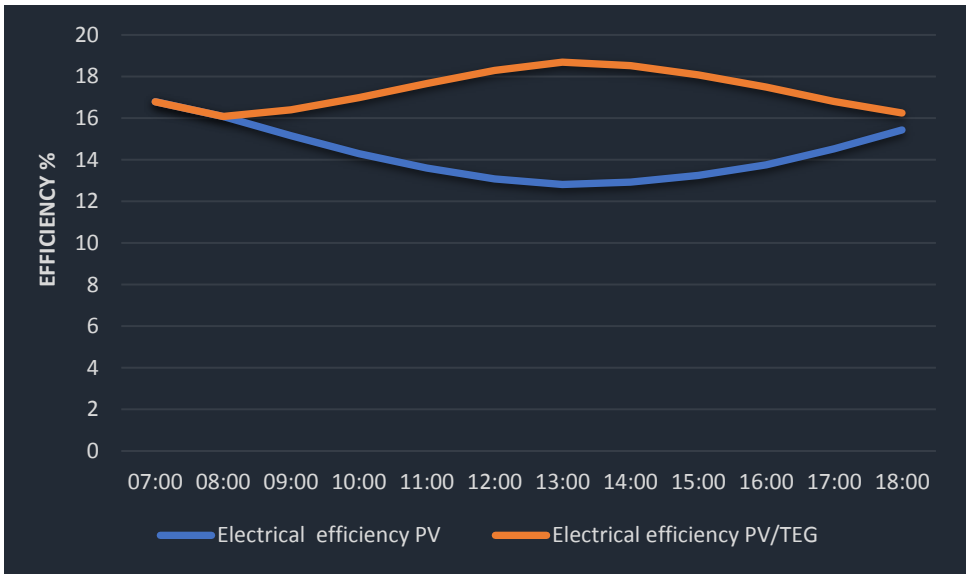

Figure 4.17 Comparison between PV panel and PV/TEG efficiency January 2019

The simulation run under January conditions, the addition of TEG allow a maximum addition of 5.88% in the overall efficiency (see Fig. 4.17). Both the hybrid and the stand alone got their efficiency dropping at the same rate until the TEG start producing power, from then the hybrid's efficiency start to rise. And under the climatic conditions of September an extra addition of 6.3% for the hybrid was achieved (see Fig. 4.19).

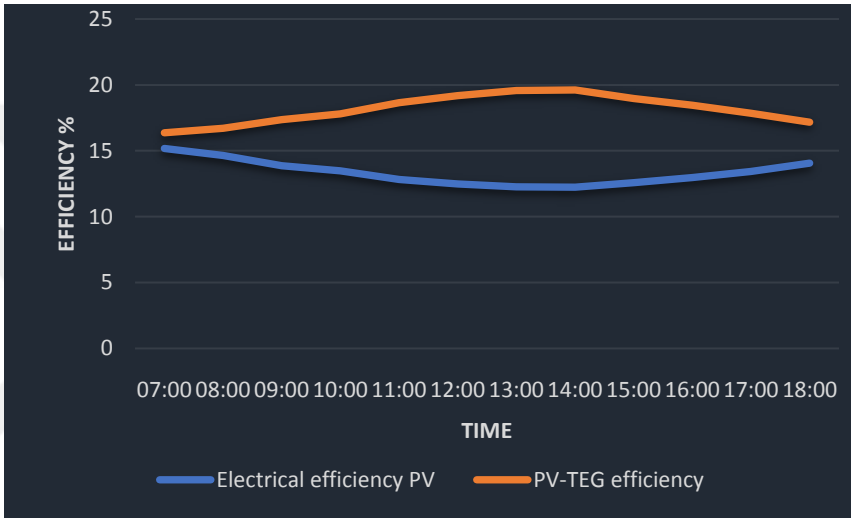

Figure 4.18 Comparison between PV panel and PV/TEG efficiency on 7th May 2019

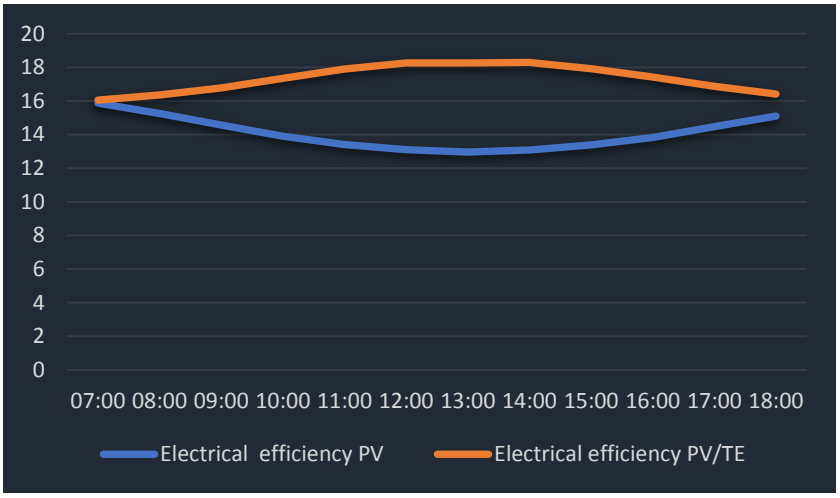

Figure 4.19 Comparison between PV panel and PV/TEG efficiency on September 2019

CHAPTER 5

CONCLUSION

It is primordial to come up with new energy sources that are ecological in order to preserve the world biodiversity and reduce the production of carbon dioxide. The harvest of solar energy is one of the best alternatives. The most common way to exploit solar energy is the use of a PV panels. Nevertheless, the efficiency of these panels is affected by the cell temperature: the higher the cell temperature is the lower the PV efficiency gets. Thus, the improvement of the efficiency of the PV is the aim of many researchers. Many tests and researches were conducted to enhance the efficiency of the PV panel. That is how the idea of creating a PV/TEG hybrid was brought up. By linking the thermoelectric module with a PV module, it allows to exploit the heating of the panel in order to provide an additional power by using that heat. Our work was conducted using data from Niger, it is the first study of this sort conducted in the country. Niger presents a very good potential when it comes to solar energy. Nevertheless, the country faces difficulties to provide the population with stable energy, which is a holdback for the development in a world run by energy. This work can be the foundation or the start for the exploitation of this system in the country, which would lead Niger to an energy independence thus to the development of the country.

The result of our work is consistent with the previous work and has shown a rise in the power output of the PV panel when combined with the TEG. It was proven that the hybrid presents a superior efficiency when compared to the PV stand alone. The influence of the irradiance, and the PV panel's temperature were also demonstrated for both the PV panel and the TEG. When the cell temperature was at its highest, the hybrid showed an efficiency of 19.57% which is greater than the one of the PV stand-alone whose efficiency is of the value of 12.26%.

In the future it would be interesting to combined different new technology that showed great results to create a better hybrid. For example, make an hybrid PV/TE using a GaAs-based solar cell, use a coper plate as a concentrator in the thermoelectric generator. To this configuration it can be considered adding a hot water tube using nanofluids as it was seen that combining the hybrid with a HW also enhance the effectiveness. The PV/TE system should also be experimentally tested in Niger to support this work and be able to compare the results with the one calculated theoretically.

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