ANKARA YILDIRIM BEYAZIT UNIVERSITY

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PERFORMANCE ANALYSIS OF PHOTOVOLTAIC-THERMAL (PV/T) SOLAR SYSTEMS

M.Sc. Thesis by

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Mariama Ali GARBA

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M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"PERFORMANCE ANALYSIS OF PHOTOVOLTAIC-THERMAL (PV/T) SOLAR SYSTEMS "** completed by **MARIAMA ALI GARBA** under the supervision of **DR. BULENT YESİLATA** 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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PERFORMANCE ANALYSIS OF PHOTOVOLTAIC-THERMAL (PV/T) SOLAR SYSTEMS

ABSTRACT

Hybrid Photovoltaic/Thermal systems, also called as PV/T systems or solar cogeneration systems, are innovative power generation technologies that convert solar radiation into usable thermal and electrical energy. Such systems combine a solar photovoltaic module, which convert sunlight into electricity, with a solar thermal collector, which captures the remaining energy and removes waste heat from PV module. The performance of PV/T system is higher than that of PV module. To improve the performance of PV/T systems a lot of the studies have been done and researchers keep on investigating these systems.

A comprehensive review on these previous research studies are presented here. Many methods and approaches to enhance the performance of the PV/T systems are discussed along with the mathematical models used. 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/T systems based on nanofluids are exist. Therefore, comprehensive experimental studies under real atmospheric conditions should be done with these systems, without neglecting effects of variations in mass flow rate of nanofluids.

The aim of our study is to investigate the performance of PV/T systems under the climatic conditions of Niamey the capital city of Niger. Niger has a great solar potential with a monthly average irradiation of 9 hours. Thus, a theoretical study was conducted, followed by a comparison of the performance of PV/T system with stand-alone PV module. The obtained results were consistent with the previous works on these systems. The electrical efficiency of the PV/T system increases by 0.1 percent per degree Celsius, and the cell temperature decreased by 15 degree Celsius. In addition, the useful heat and instantaneous thermal efficiency were calculated to be 648.27 W and 66.69 percent, respectively.

Keywords: PV/T, PV/T-PCM , Solar energy, PV hybrid, renewable energy

HİBRİT FOTOVOLTAİK-ISIL (PV/T) SİSTEMLERİN PERFORMANS ANALİZİ

ÖZET

PV/T sistemleri veya güneş kojenerasyon sistemleri olarak da adlandırılan hibrid Fotovoltaik / Termal sistemler, güneş radyasyonunu kullanılabilir termal ve elektrik enerjisine dönüştüren yenilikçi güç üretim teknolojileridir. Bu tür sistemler, güneş ışığını elektriğe dönüştüren bir güneş fotovoltaik modülünü, kalan enerjiyi yakalayan ve PV modülünden atık ısıyı uzaklaştıran bir güneş termal toplayıcı ile birleştirir. PV/T sisteminin performansı PV modülünden daha yüksektir. PV/T sistemlerinin performansını artırmak için birçok çalışma yapılmış ve araştırmacılar araştırmaya devam etmektedir.

Bu önceki araştırma çalışmaları hakkında kapsamlı bir inceleme burada sunulmuştur. PV/T sistemlerinin performansını artırmak için kullanılan birçok yöntem ve yaklaşım, kullanılan matematiksel modellerle birlikte tartışılmıştır. Literatürdeki mevcut boşlukları tanımlanmış ve gelecekteki araştırmalar için yön verici öneriler verilmiştir. Burada, nanoakışkanlara dayanan PV/T sistemleri üzerinde sadece birkaç deneysel çalışmanın mevcut olduğu vurgulanmaktadır. Bu nedenle, bu sistemlerle, nanoakışkanlara kütle akış hızındaki değişimlerin etkileri göz ardı edilmeden, gerçek atmosfer koşulları altında kapsamlı deneysel çalışmalar yapılmalıdır.

Çalışmamızın amacı Nijer'in başkenti Niamey iklim koşullarında PV/T sistemlerinin performansını incelemektir. Nijer, aylık ortalama 9 saatlik ışınlama ile büyük bir güneşlenme potansiyeline sahiptir. Böylece teorik bir çalışma yapılmış, bunu PV/T sisteminin performansının bağımsız PV modülü ile karşılaştırması yapılmıştır. Elde edilen sonuçlar, bu sistemlerde daha önce yapılmış olan çalışmalarla çelişkili yönü bulunmamıştır. PV / T sisteminin elektrik verimliliği, derece Santigrat başına yüzde 0,1 artar, hücre sıcaklığı 15 derece azalmıştır. Ayrıca, faydalı ısı ve anlık termal verim sırasıyla 648.27 Watt ve %66,69 olarak hesaplanmıştır.

Anahtar Kelimeler: PVT, PV/T-PCM, Güneş enerjisi, PV hibrid, yenilenebilir enerji

CONTENTS

NOMENCLATURE

Roman Letter Symbols

A	Diode ideality
A_c	Collector area
C_p	Specific heat capacity
D	Outer diameter of tube
F_R	Heat removal factor
F	Standard fin efficiency
FF	Fill Factor
F'	Efficiency factor
G	Total solar irradiation
h_w	Convection heat transfer coefficient
h_{fi}	Heat transfer coefficient inside tube
I	Current
I_0	Saturation current
k_{edge}	Thermal conductivity of edge
k_{ins}	Thermal conductivity of insulator
L_{edge}	Thickness of the edge
L_{ins}	Thickness of the insulator
m	Mass flow rate
N_s	Number of PV cell in series
N	Glass cover number
p	Collector circumference
P	Power
PF	Packing factor
q	Charge of electron
Q_{th}	Useful heat
Q_u	Useful gain energy
T	Temperature
t	Absorber plate thickness

U_L	Overall heat loss coefficient
V_t	Thermal voltage
V	Voltage
V_{wind}	Wind velocity
W	Distance between the tube
x	Length of the tube

Greek Letter Symbols

η	Efficiency
β	Temperature coefficient of the PV module
ε_p	Emissivity of plate
ε_g	Emissivity of glass
α_{cell}	Absorptivity of photovoltaic cells
ρ_f	Density of the fluid
τ_g	Transmissivity of the glass cover
ΔP	Pressure drops of the coolant
θ	Collector tilt

Subscripts

d	Diode
el	Electric
f	Fluid
in	inlet
max	Maximum
Out	Output
oc	Open Circuit
p	Pump
ph	Photovoltaic
r	reference
sc	Short Circuit
th	Thermal

Acronyms

CPV	Concentrated Photovoltaic
DNI	Direct normal irradiance
HCPV	High concentration photovoltaic
ICSSWH	Integrated collector storage solar water heater
LCPV	Low concentration photovoltaic
MPP	Maximum Power Point
MSE	Single-diode-model
MWCNT	Multi-walled carbon nanotube
PV/T	Photovoltaic-thermal system
PV	Photovoltaic module
PCM	Phase Change Material
PPP	Photovoltaic Power
PHP	Pulsating heat pipe
STC	Solar thermal collector

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CHAPTER 1

INTRODUCTION

1.1 Main Framework

With the increase of the population, the demand of energy increases rapidly all over the world. Thus, to be able to meet the demand in energy, renewable energies, solar energy in particular, is used . It has been shown that the energy received by Earth from the sun in a day is thirty times greater than the yearly global energy consumption. Solar energy may produce heat and power depending on the solar conversion technology used.

Solar photovoltaic (PV) systems consist of many cells to convert sunlight into electricity. Their working principle is based on photovoltaic effect. During this process, light (solar rays) are absorbed by some special material causing the release of an electron. This process happens solely in particular materials called semiconductors such as silicon, in the form of monocrystalline, polycrystalline, and amorphous, and cadmium telluride. In order to achieve the desired values of current and voltage, these soar cells are consolidated in larger structures called solar panels/modules. The main problem that encountered with PV cells is the increase of the temperature during operation, resulting in decrease in its efficiency. Solar thermal, on the other hand, makes use of the sunlight to heat a fluid which can be water or any kind of fluid regarding the application. Its working principle is based on direct heating of fluid using the sunlight, the fluid in the tubes is heated up and carried into a storage tank for utilization.

By analyzing these two technologies, it is found that solar thermal can be up to 70% more efficient in the process of collecting heat from sun rays than solar PV. However, during winter solar thermal is less effective because the sun radiation is not strong. Merging these two technologies into a hybrid module is found to be complementary and combines advantages of each. This type of combined solar module technology is known as hybrid photovoltaic-thermal (PV/T) solar system. Hybrid PV/T systems

accordingly transform sunlight into thermal and electrical energy. The PV cell converts the solar radiation into electricity, while the solar thermal collector is responsible transporting heat away from PV cells. Cooling the PV cells enhances electrical power output by reducing the electrical losses, while at the same time the thermal part of the hybrid module produces hot water for residential / industrial use.

The PV/T collectors is thus an important solution to reach a better exploitation for the solar energy. These systems can generate more energy per unit surface area by comparing them to PV modules and solar thermal collectors separately. After the absorption of sunlight by a PV panel, approximatively 15-20% of the solar power is transformed into electrical output. The remaining solar energy is turning up heating the PV cells, which engender many problems. The deterioration of the electrical efficiency for example takes place due to augmentation of the temperature within the cell. The exact decrease rate depends not only on the climate but also on the materials. Therefore, in area or site where the climatic conditions are extreme, and the temperatures are high mostly in summer, a significant increase of the deterioration of the electrical efficiency was observed [1]. Another problem arisen from high temperature inside the cell is complete destruction due to the overheating. By consequent, cooling the PV panels becomes imperative thing to accomplish. Cooling of PV can be beneficial not only by enhancing the electrical efficiency, but also by making use of the thermal energy for other application such as heating water or any fluid. Thus, hybrid PV/T modules have taken great interests from academia and industry as comprehensively discussed in the next section.

In this study, we are going to make analytical analysis for the performance of the photovoltaic thermal systems under the climatic conditions of Niger, particularly in Niamey city. During this investigation, the electrical efficiency of the PV panel in the PV/T system is calculated and compared with the stand-alone PV panel. Furthermore, the thermal efficiency as well as the overall efficiency the system will be analyzed.

1.2 Solar Potential in Niger

Niger is reported to be among the sunniest and hottest countries in the world as shown by the Fig. 1.1 and Fig.1.2. This situation is due to its position near the equator. The highest temperature is recorded to be 46℃ whereas, the lowest temperature is 26℃.

This country presents a huge solar potential, with the monthly average insolation hours of 9, as shown in Fig. 1.3. In their study, Maigargue D. et al. [2] investigated the solar potential of Niamey in 2015 and 2016. They reported that the amount of irradiance changed from 5.1 kWh/m^2 to 6.3 kWh/m^2, which are significantly high. The sunniest months were April, May, September, and October, and December, January and August were the low irradiation months. They concluded that the city is favorable for different energy applications.

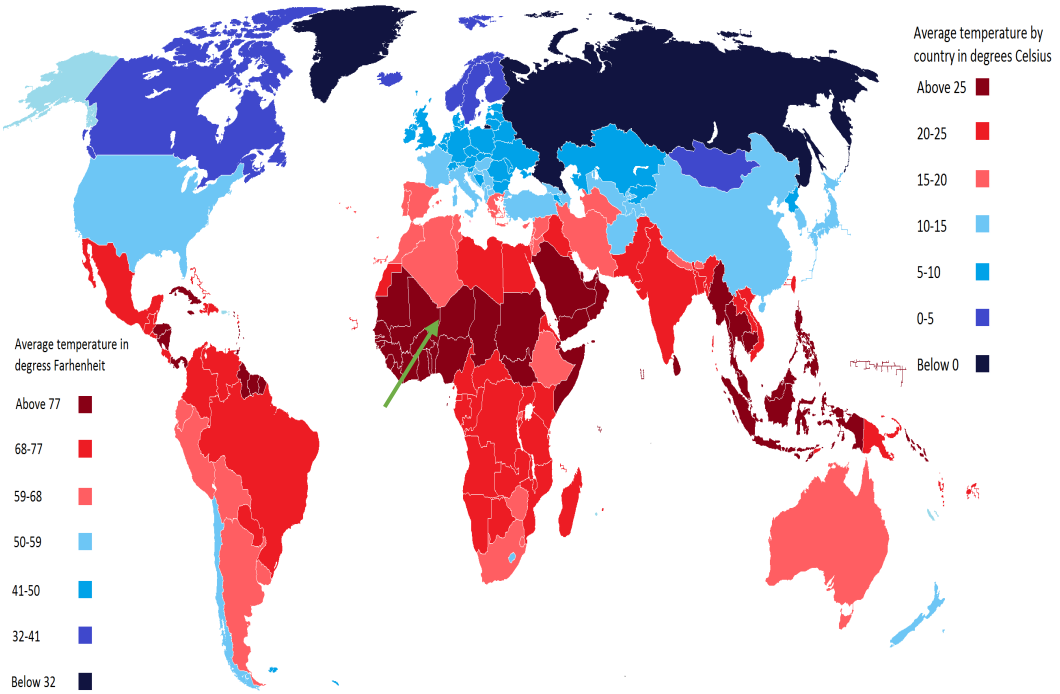


Figure 1.1 Hottest countries in the World [3].

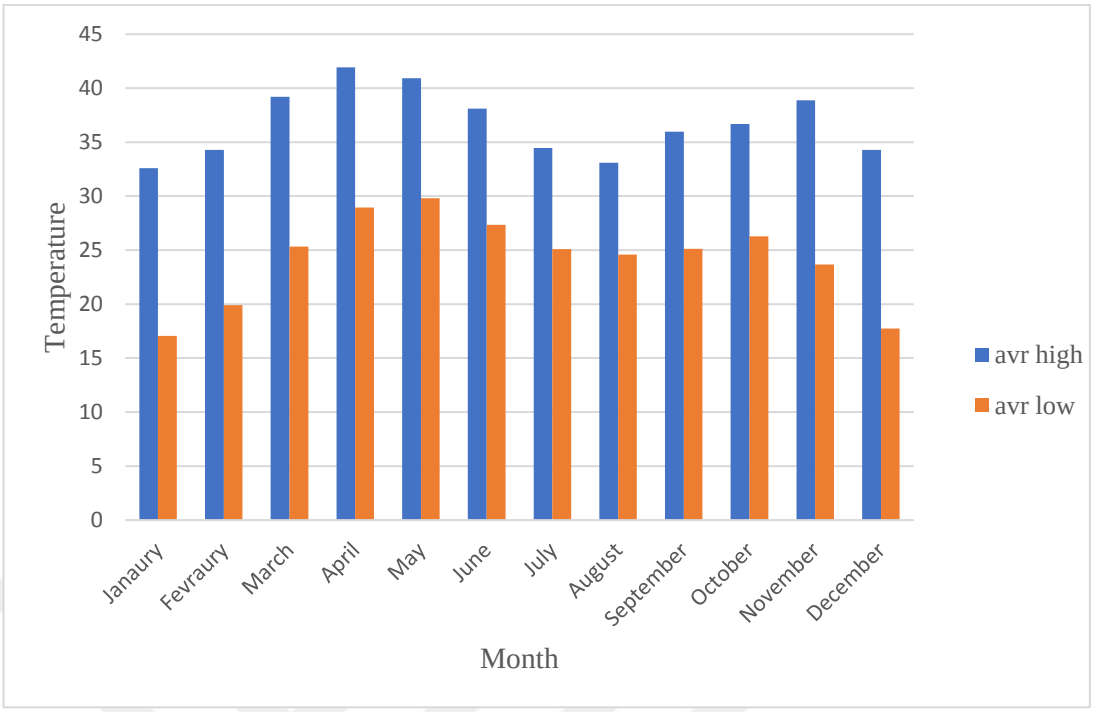


Figure 1.2 Average monthly temperature in Niamey city.

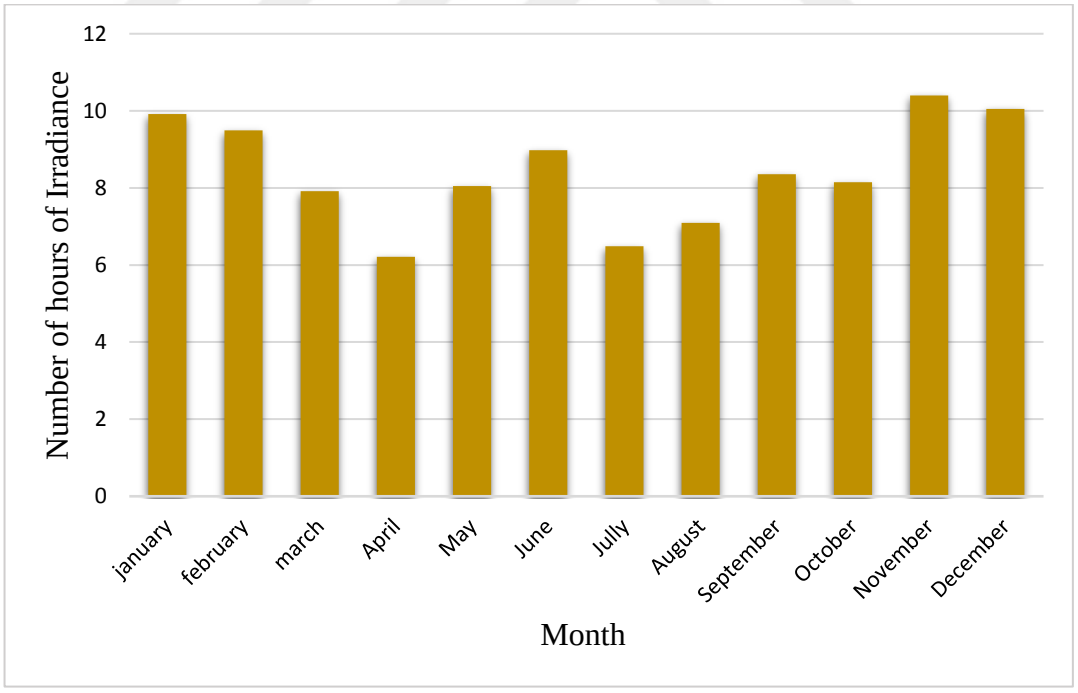


Figure 1.3 Average monthly hours of irradiance in Niamey

In 2019, it was reported that the Direct Normal Irradiance (DNI) of Niger varies from 4.2 kWh/m^2 to 7 kWh/m^2, as shown in Fig. 1.4. The highest DNI is measured in the north part , while the lowest DNI is in the south.

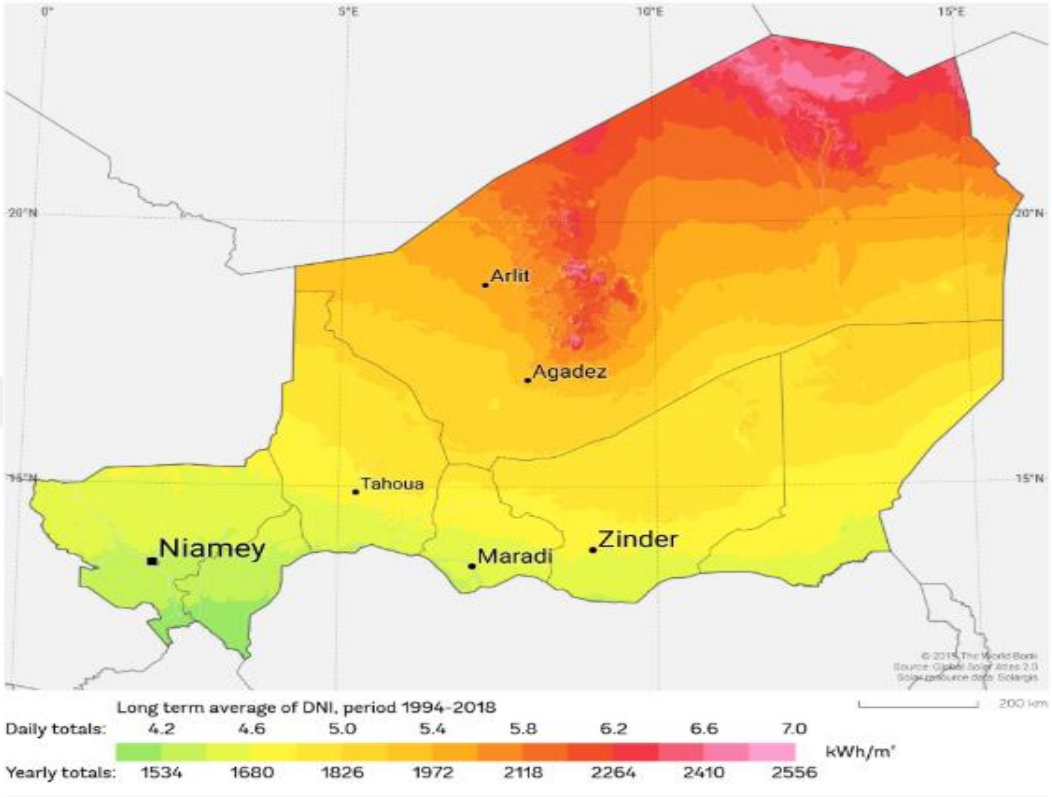


Figure 1.4 Variation of direct normal irradiance in Niger [4].

The daily PV power potential varies between 4.6 kWh/kWp to 5.6 kWh/kWp from the south to the north part. The highest annual PV power potential is recorded to be 2045 kWh/kWp in the north. For small residential PV system, the annual average of PV power output is measured to be between 1.605 MWh and 2178 kWh/m^2 per year, as shown in Fig. 1.5.

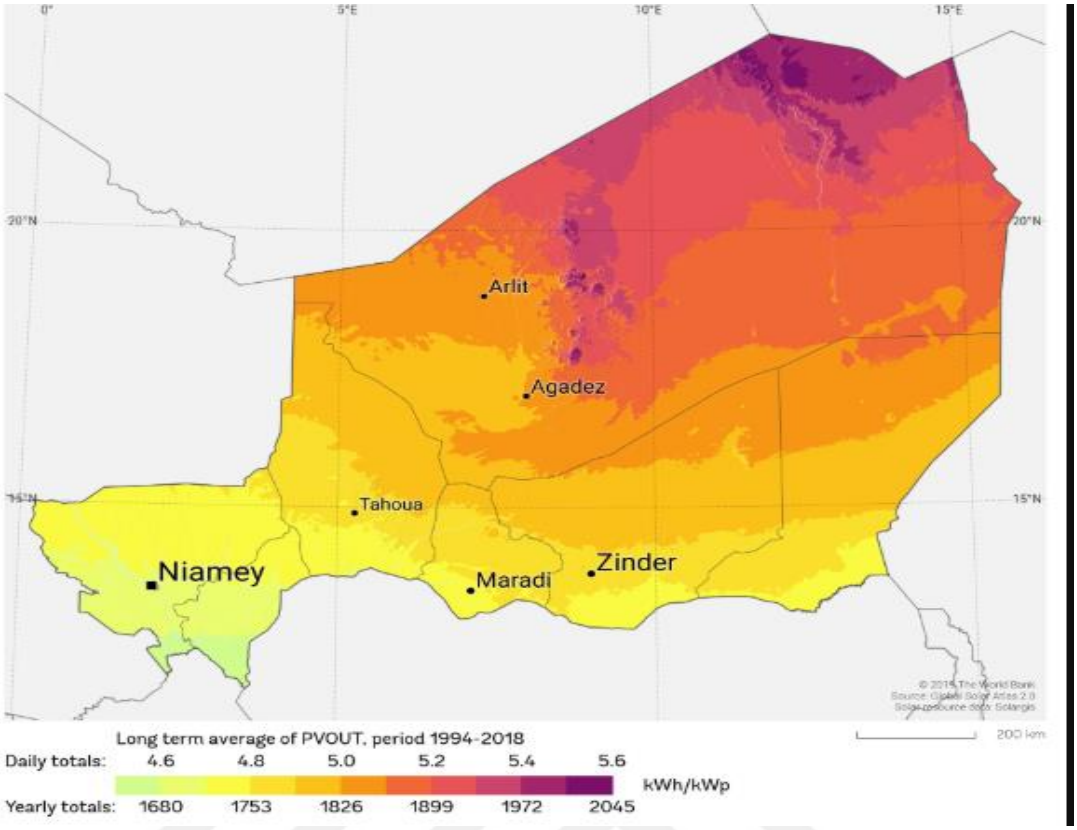


Figure 1.5 Distribution of PV power potential in Niger [4].

Like DNI, high concentration of global horizontal irradiation (GHI) is determined in the north as shown in Fig. 1.6.

With a land area of 1 270 000 km^2, Niger is the largest country in the West Africa. Given the vastness of the country, and its very low population density (7 inhabitants/ km^2), the development of a centralized electrical network based on solar energy may allow Niger to be independent in the energy sector. Considering an average daily insolation of 6 kWh/m^2, and annual electrical consumption of 465 GWh, the electrical need of the entire country will be covered with an area of 1.4 km^2 of photovoltaic panels. This area represents only 0.00011% of the land area of the country or around 0.00017% of the desert surface. Thus, Niger has an enormous solar potential in order to meet the demand of the energy.

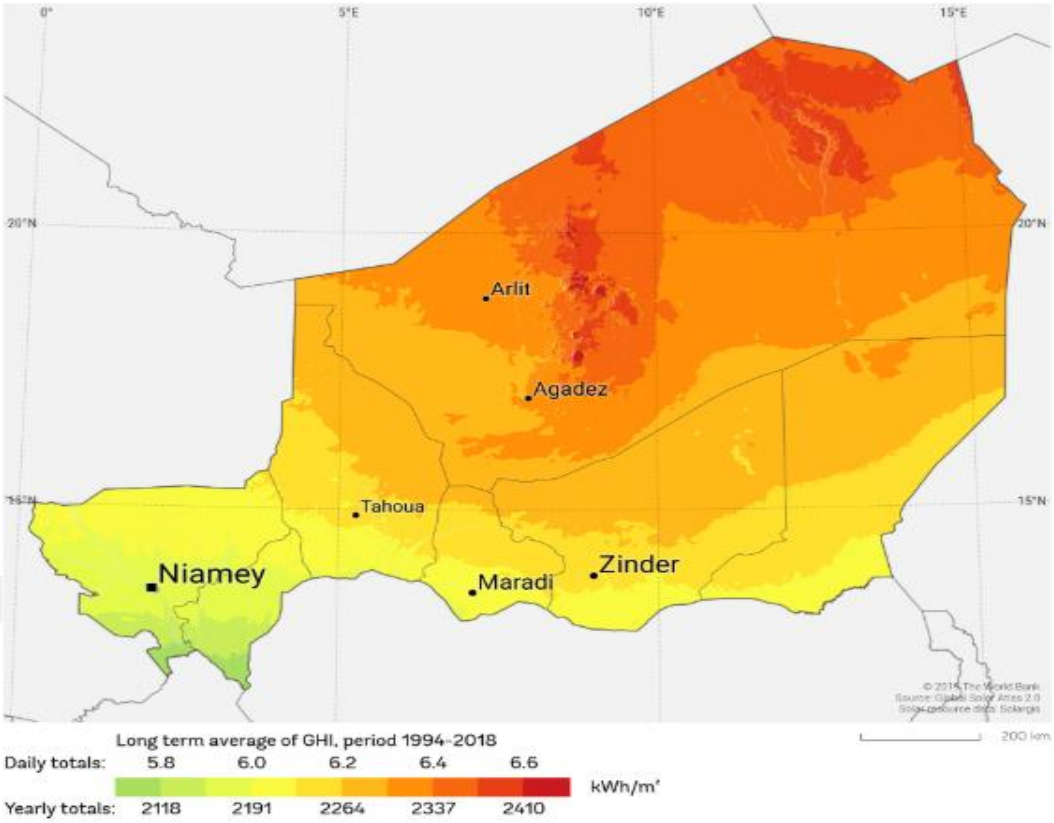


Figure 1.6 Distribution of horizontal irradiance in Niger [4] .

1.3 Working Principle Of PV/T Systems

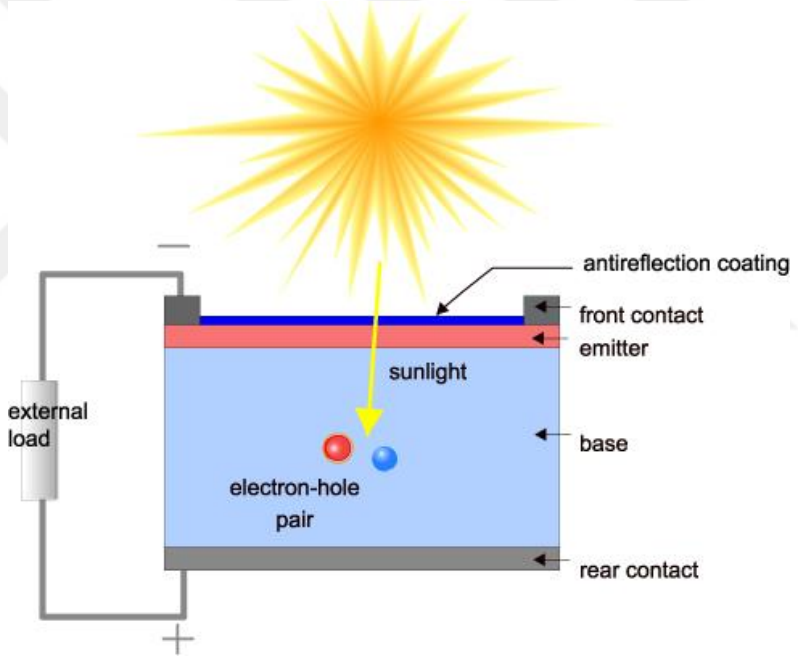
1.3.1 Solar Cell Operation

A solar cell is made of silicon that is a semiconductor which normally don't conduct electricity, but under certain conditions, it can do so. Solar cell is the junction of two different layers of silicon that have been specially treated or doped so they will let electricity flow through them in a particular way. P-type or positive type silicon is the lower layer that has slightly too few electrons. The upper layer is negative type silicon and has slightly too many electrons. When we place a layer of n-type silicon on a layer of p-type silicon, a barrier is created at the junction of the two materials. And no electron can cross the barrier, this junction

The working principle of a solar cell is based on photovoltaic effect. When light falls on a solar cell, electrons in the absorber layer are excited from a lower-energy "ground

state," in which they are bound to specific atoms in the solid, to a higher "excited state," in which they can move through the solid. The empty space left by electrons when they moved in the conduction band is called holes, hence several electrons-holes are created. Due to the charge present in the PN junction, they are deflected in opposite side creating a voltage. The barrier created at the junction of the two materials induces a built-in electric field that produces the photovoltaic effect. In effect, the electric field gives a collective motion to the electrons that flow past the electrical contact layers into an external circuit where they can do useful work.

These cells are combined in series for the panel. Cells are usually combined in series to boost the voltage or in parallel to increase the current.



1.3.2 PV/T System Operation

Solar cell used the property of the light to generate electricity. During this process, the cell keeps on heating up due to the exposure to sun radiation. 80% of the sun radiation is heat, just 20% is used to electricity production. This heat will decrease the efficiency of the PV panel because as the temperature increases, the generated electricity decreases. Also, the solar panel life is decreased due to surface heating effect. Thus, copper tubes are used to circulate the water behind the panel so that the surface heat is extracted from the panel and this thermal energy is used to generated hot water. A

pump can be used to circulate the water inside the tube. This will enhance the efficiency of the PV panel.

1.4 Types of PV/T Collectors

PV/T solar energy devices can be categorized into 3 types depending on their operating temperature: when the temperature reaches up to 50°C, they are called low temperature system, medium system temperature is up to 80°C, and when the temperature exceeds 80°C they are characterized as high temperature systems. The most practical PV/T types related to air or water preheating are the hybrid photovoltaic/thermal devices that are operating at low temperatures. The PV/T systems that utilizes photovoltaic modules and supplied heat at high temperature (greater than 80°C) present some lamination issues owing to larger operating temperatures. The basic forms of the PV/T collectors are the followings: Flat-plate PV/T Liquid collectors, Flat-plate PV/T air collectors, Flat-plate PV/T liquid and air collectors, and PV/T Concentrator collectors.

The flat-plate PV/T liquid collector can be divided into two types: the glazed PV/T collectors which possess a glass covering PV module, and they generate more thermal energy and small electrical energy. The second type is the unglazed PV/T collectors called also uncovered PV/T collectors, which have lower thermal energy and larger electrical efficiency. JinHee et al. [5] evaluated the thermal and electrical efficiencies of those PV/T collectors. The result demonstrated that the thermal performance of the Glazed PV / Thermal collector is 14% greater than that of the uncovered collector. However, the electrical efficiency of the unglazed PV/T collector is 1.4% greater than that of the glazed one. The total energy efficiency of the collectors was compared by adding the average values of electrical and thermal performance. And it was recorded that the glazed PV/ Thermal collector possesses an overall efficiency of 48.4%, while the unglazed one was 35.8% .

1.4.1 PV/T Water Collectors

PV/ T water collectors are consisted of solar radiation absorber, a thermal insulation, and a glazing to maintain the thermal losses low from the surface of the system that is exposed to sun (see Fig. 1.7). The absorber is constituted of a heat extraction unit for

water or air circulation. To allow a heat transfer from the cells to the absorber plate and at the same time to avoid short circuiting the cells, a material that possesses good thermal conductivity and weak electrical conductivity was utilized. Metallic absorber plates along with pipes for water flow are mostly utilized by PV/T water devices. The water flows within the pipes which are connected to the absorber plate rear surface and gathers the heat from the absorber. To minimize heat loss from the surfaces, the back and sides of the collector are insulated. It was recorded that the PV/T water devices can work with forced circulation by a pump or by ordinary flow of the heat transfer fluid. Other idea related to the water circulation and heat recuperation consists to move it inside flat channels above and under photovoltaic module.

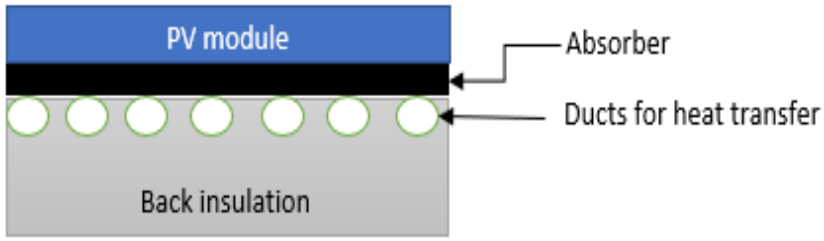


Figure 1.7 Schematic of PV/T-water collector

1.4.2 PV/T Air Collectors

In PV/T air collectors, the absorbers are the PV modules. The location of the air duct is less significant, where it can be connected behind, over the PV modules (see Fig 1.8). When the photovoltaic module is heated by the incident solar radiation, some part is moved to the air channel via convection and radiation. Heat energy is transported by radiation heat from photovoltaic rear surface to the back wall of the air channel. As result, its temperature increases. Using convention, the total radiant heat received by the back wall is moved to the airflow. A small part of this heat is lost to the atmosphere via the back insulation. By consequent, heat is produced through hot air. This hot air is the combination of the heat from the rear surface of the photovoltaic module and the back wall. İn daytime, its temperature increases. The airflow mode and rate, channel depth, determined the thermal efficiency.

Fig. 1.9 shows the repartition of the three types of collector mentioned previously.

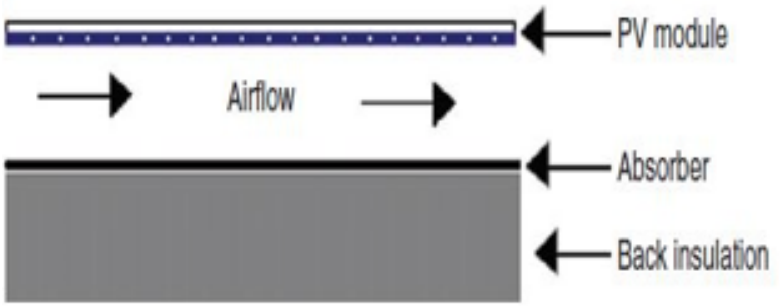


Figure 1.8 Schematic of PV/T-air collector

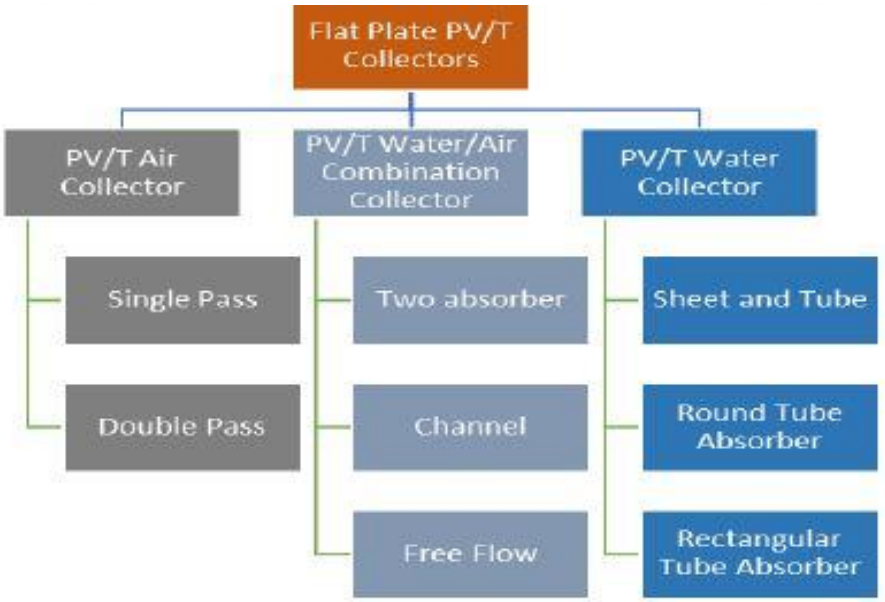


Figure 1.9 Classification of PV/T Collectors

1.4.3 PV/T Concentrators

Concentrator devices possess the advantage to diminish the number of PV cell needed. They utilized lenses or curved mirror to focus solar radiation on small, greatly efficient multi-junction PV cells. Moreover, concentrators devices need good control devices to precisely track the sun and to prevent the photovoltaic cells from damaging when the temperature is too high. They can convert 75% of the incoming solar radiation into electricity and heat. There exist two types of concentrators: low concentration photovoltaic (LCPV) and high concentration photovoltaic (HCPV).

Low concentration photovoltaic devices (LCPV) are devices which solar concentration is in the range of 2-100 suns. The cells do not require any active cooling because the heat flux is small. Also, standard PV modules do not require any tracking or cooling change. LCPV devices comport a booster reflector which can enhance the electric output more than 30%.

High concentration photovoltaics (HCPV) use concentrating optics which include dish reflectors or Fresnel lenses. These devices centralize the solar radiation to intensities of 1000 suns or even more. The photovoltaic cells need large heat capacity sinks to avoid not only thermal abolition but also to contain the temperature that can affect the electrical efficiency. To increase the total conversion efficiency, the heat sink must be passive. This part is related to the cooling model.

CHAPTER 2

PREVIOUS WORK

2.1 Discussion of Previous Research Studies

Discussion of previous studies regarding with PV/T systems was comprehensively performed by M. A. Garba and B. Yeşilata [6], who are respectively writer and advisor of this thesis, published a proceedings paper[1], as an earlier output of this thesis work. Instead of repeating the same discussion here, brief highlights of the most recent and relevant works are summarized in Table 2.1 below:

Table 2.1 A brief highlights of the most recent studies on PV/T systems

Ref.#	Authors (Year)	Material /System	Method /Application	Summary of results
[7]	Brahim, T. and A. Jemni (2017)	PV/T in general	Economical assessment and applications	Efficiency increase by removing excess heat is not enough. Excess heat must be used for heating and cooling purposes to make the system economically attractive
[8]	Ramos, A., et al. (2017)	PV/T system for heating, cooling	Economic analysis and Numerical(TRNSYS)	Numerical study was done using TRNSYS. An overall cost of energy is 0.12 euro per kWh, with 60% of the hot water demand covered.

[1] M. A. Garba and B. Yeşilata, "Use of Hybrid Photovoltaic-Thermal (PV/T) Solar Modules for Enhancing Overall System Efficiency," 2019 3rd International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT), Ankara, Turkey, 2019, pp. 1-10, doi: 10.1109/ISMSIT.2019.8932918.

Table 2.1 (continued.) A brief highlights of the most recent studies on PV/T systems

Ref.#	Authors (Year)	Material /System	Method /Application	Summary of results
[9]	Smyth, M., et al. (2018)	PV/T Façade module	Experimental study	Using PV/T system in integrated collector storage, the heat retention was 23.6% and overall efficiency is 65%.
[10]	Hossain et al. (2019)	PV/T with water flowing in parallel serpentine pipe	Experimental	High thermal efficiency up to 76.58% can be reached. The increase in electrical efficiency remains low, nearly 1%.
[11]	Abdallah, S.R. et al. (2019)	PV/T system using low concentration MWCNT nanofluid	Experimental	The performance of PV/T system using MWCNT water at different concentrations was tested. At concentration of 0.075% of nanofluid, an overall efficiency of 61.23% was recorded, and cell temperature was decreased by 10.3C.
[12]	P.L. Paradis et al. (2018)	PV/T collector using an evaporator in a CO_2 transcrital	Numerical heat transfer design	The electrical efficiency was enhanced from 14% to 16%, and thermal efficiency was 56.3%.

Table 2.1 (continued.) A brief highlights of the most recent studies on PV/T systems

Ref.#	Authors (Year)	Material /System	Method /Application	Summary of results
[13]	Zhang et al. (2019)	Flat-plate and low concentrating PV/T (up to 4)	Experimental	Electrical power and useful heat outputs can be increase up to three by using low concentrating PV/T system
[14]	Sarafraz et al. (2019)	PCM integrated PV/T with nano-fluid of water/ ethylene- glycol	Experimental	Presence of PCM and nanofluid can contribute obtaining the highest electrical and thermal efficiencies at an relatively lower irradiance of 291.1 W/m².
[15]	Diallo, T.M., et al. (2019)	PV/T system utilizing loop heat pipe with micro-channel evaporator and PCM	Numerical analysis	They reported a thermal and electrical efficiencies of 55.6% and 12.2%. The overall efficiency of the system was 67.8%, and COP was 2.2 times greater than a conventional one.
[16]	AL-Musawi, A.I.A., et al. (2019)	PV/T system with nanoPCM (SiO water nanofluid/ PCM)material	Numerical	With a reduction of 16 C of the cell temperature, an increment of 8% and 25% of electrical and thermal efficiencies,respectively, were reported.

Table 2.1 (continued.) A brief highlights of the most recent studies on PV/T systems

Ref.#	Authors (Year)	Material /System	Method /Application	Summary of results
[17]	Balotaki and Saidi (2019)	PV/T with Pulsating Heat Pipe	Experimental	The pulsating heat pipe contributes increasing system performance depending on its position and inclination
[18]	Ashikuzzaman, M., et al. (2019)	3D design of PV/T-PCM system	Numerical using finite element method	The electrical and thermal efficiencies were 13.6% and 66.7% respectively.
[19]	Simón-Allué, R., et al. (2019)	PV/T-PCM system	Experimental	The enhancement of heat production was up to 30%.
[20]	Yu, Y., et al. (2019)	Unglazed PV/T system	Eperimental and TRNSYS simulations	The electrical efficiency varied from 10.3% to 13%. The thermal efficiency was 70%.

Table 2.1 (continued.) A brief highlights of the most recent studies on PV/T systems

Ref.#	Authors (Year)	Material /System	Method /Application	Summary of results
[21]	Poonia, S. et al. (2018)	PV/T system for drying fruit	Economic investigation	Better products were obtained with the efficiency of dryer equaled to 16.7%. The maximum value of IRR of the system was 54.5%.
[22]	Hader, M. and W. Al- Kouz (2019)	PV/T system with Al2O3-H2O nanofluid and fins	Numerical analysis via COMSOL software	The overall efficiency of the system increased with the increase of the fin lenght and the nanofluid volume. Thus, an overall efficiency of 84.2% was obtained.
[23]	Bigorajski et al. (2019)	Micro PV/T system	Experimental	During winter, the generation of the thermal and electrical energy was higher than that of summmer.
[24]	Agathokleous, R.A. et al. (2018)	Building coupled with PV/T system	Experimental	The energy efficiency of the system was in the range of 26.5% to 33.5%. The exergy efficiency was around 13-16%.
[25]	Du, M. et al. (2019)	PV/T system using plasmonic nanofluids and silica aerogel	Theorical study	The exergy output of the system was improved by 13.3%.

Table 2.1 (continued.) A brief highlights of the most recent studies on PV/T systems

Ref.#	Authors (Year)	Material /System	Method /Application	Summary of results
[26]	Younis, A., et al. (2018)	PV/T system with Al2O3-ZnO water nanofluid	Theoritical and Experimental	At a concentration of 0.05 wt%, the energy and exergy efficiencies of the system were improved by 4.1% and 4.6% respectively.
[27]	Zarrella, A., et al. (2019)	PV/T system including a new lumped parameter design	Numerical using TRNSYS and experimental	The deviation between the simulation and measured results was 10 % for the electrical energy and around 20-30% for thermal energy.
[28]	Wu et al. (2019)	PV/T with air	Numerical	Air at lower temperature must be maintained to obtain maximum benefit if cooling is provided below of PV panels
[29]	Kazem, H.A. (2019)	PV/T with water	Experiments under outdoor conditions of Oman	Electrical efficiency of PV/T can increase up to 6%.
[30]	Gagliano et al. (2019)	Unglazed PV/T with water	Experimental and Numerical under Mediterranean	Thermal and electrical efficiencies of PV/T can be better balanced with flexible operation. Numerical errors are 12.04%

In contrast to the most of the previous studies discussed in our previous proceeding paper [6] and in Table 2.1 given above, this thesis work focus on analyzing the performance of PV/T water collector under the climatic weather conditions of Niamey city through a theorical study. This study is the first one to be done in Niger, and weather data are used for the numerical computations.

CHAPTER 3

MATHEMATICAL MODELS AND SIMULATION

3.1 PV Cell Modeling

The efficiency of photovoltaic module is calculated by analyzing the mathematical model. Therefore, there are a numerous model, some more complex than the others. In this case, a simple model of PV module is analyzed as shown in Fig. 3.1, and three parameters are determined: the open circuit voltage V_{oc} , short circuit current I_{sc}, and the efficiency n .

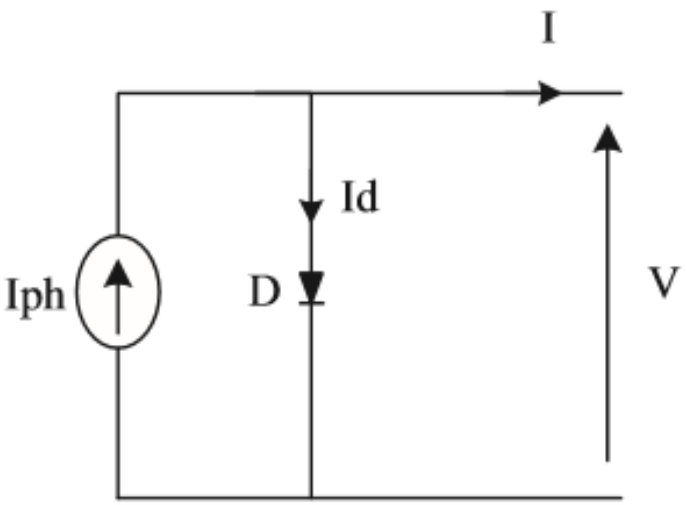


Figure 3.1 Electrical circuit of a solar cell [31]

The total current of the solar cell is expressed as:

$$I = I_{ph} - I_d \quad \textbf{(3.1)}$$

Where $\boldsymbol{I_{ph}}$the photo-current is generated by solar cell, and I_d is the diode current which is calculated as follows:

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

By substituting equation (3.5) in equation (3.4), we get:

$$I = I_{ph} - I_0 \left(e^{\frac{V}{V_t}} - 1\right) \quad \textbf{(3.3)}$$

The short circuit current is calculated when there is no voltage in the circuit, while the open circuit is determined when there is no current in the circuit. They are expressed by the following formulas:

$$I_{sc} = I_{ph}|_{V=0} \quad \textbf{(3.4)}$$

$$V_{oc} = \frac{1}{V_t} \ln\left(\frac{I_{ph}}{I_0} + 1\right) \quad \textbf{(3.5)}$$

Where $V_t = \frac{AkT}{q}$ is the thermal voltage.

At maximum power point (MPP), the maximum current, and the derivative of the current with respect to the voltage are determined respectively by the following equations:

$$I_m = I_{ph} - I_0 \left(e^{\frac{qV_m}{nN_S K_B}} - 1\right) \quad \textbf{(3.6)}$$

$$\frac{dI}{dV} = -\frac{qI_0}{nN_s k_B T} \exp\left(\frac{qV}{nN_S k_B T}\right) \quad \textbf{(3.7)}$$

From equation (3.10), the maximum voltage is found to be:

$$V_m = \frac{nN_S k_B T}{q} \ln\left(-\frac{nN_S k_B T}{qI_0}\left(\frac{dI}{dV}\right)_{V_m}\right) \quad \textbf{(3.8)}$$

Let us assume that the derivative in equation (3.11) can be determined by:

$$\frac{dI}{dV}|_{V_m} \cong -\frac{0 - I_{sc}}{V_{oc} - 0} = -\frac{I_{sc}}{V_{oc}} \quad \textbf{(3.9)}$$

By rewriting equations (3.11) and (3.10), V_m and I_m are expressed as:

$$V_m = \frac{nN_S k_B T}{q} \ln\left(\frac{nN_S k_B T}{qI_0}\frac{I_{sc}}{V_{oc}}\right) \quad \textbf{(3.10)}$$

$$I_m = I_{ph} + I_0 - \frac{nN_s k_B T}{q}\left(\frac{I_{sc}}{V_{oc}}\right) \quad \textbf{(3.11)}$$

The power and the maximum power of the solar cell are determined respectively by the following equations:

$$P = I_{sc}.V_{oc} \quad \textbf{(3.12)}$$

$$P_m = I_m.V_m \quad \textbf{(3.13)}$$

The efficiency of the photovoltaic module is found:

$$\eta = \frac{P_m}{P_{in}} \quad \textbf{(3.14)}$$

The efficiency can also be expressed in function of the fill factor and I_{sc} , V_{oc} :

$$\eta = FF.V_{oc}.I_{sc}/P_{in} \quad \textbf{(3.15)}$$

Where $FF = \frac{I_m.V_m}{I_{sc}.V_{oc}}$ **(3.16)**

3.2 PV Module Modelling

When exposed to sunlight, the solar cell may be modelled an equivalent electrical circuit, which contains ohmic resistors presenting the internal losses. These resistances are known as series resistance and shunt resistances as shown in Fig. 3.2. In their study, Cubas et al.[31] presented the expressions of the unknown parameters to be found in order to plot the I-V curve.

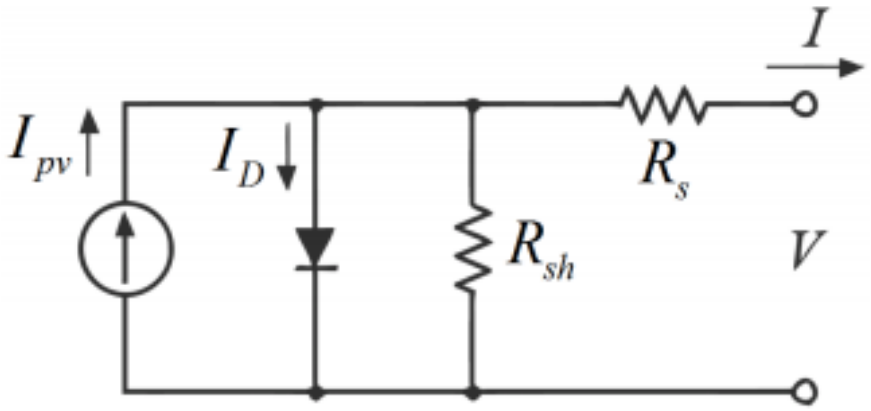


Figure 3.2 PV module equivalent circuit corresponding to the MSE modeL [31]

The first equation is the expression of the total current of the PV solar cell:

$$I = I_{pv} - I_0 \left[\left(e^{\frac{V+IR_S}{AV_t}} - 1 \right) \right] - \frac{V+IR_S}{R_{sh}} \quad \textbf{(3.17)}$$

The thermal voltage Vt is calculated as follow:

$$V_t = \frac{N_s kT}{q} \quad \textbf{(3.18)}$$

where Ns is the number of cells in series.

At short circuit , which means $I = I_{sc}$ and $V = 0$, equation 3.17 becomes:

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

At the open circuit point, satisfying the following condition $I = 0$ and $V = V_{oc}$, we obtain

$$0 = I_{pv} - I_0 \left[\left(e^{\frac{V_{oc}}{AV_t}} - 1 \right) \right] - \frac{V_{oc}}{R_{sh}} \quad \textbf{(3.20)}$$

At the MPP, the following expressions are obtained:

$$I_{max} = I_{pv} - I_0 \left[\left(e^{\frac{V_{max} + I_{max} R_s}{AV_t}} - 1 \right) \right] - \frac{V_{max} + I_{max} R_s}{R_{sh}} \quad \textbf{(3.21)}$$

$$-\frac{I_{max}}{V_{max}} = -\frac{I_o}{AV_t} . \left(1 - \frac{I_{max}}{V_{max}} R_s\right) . \left(e^{\frac{V_{max} + I_{max} R_s}{AV_t}} \right) - \frac{1}{R_{sh}} \left(1 - \frac{I_{max}}{V_{max}} R_s\right) \quad \textbf{(3.22)}$$

Taking in account the above equations, the expressions for calculating the series and shunt resistances are presented as follow:

The series resistance is found by the following equation[31]:

$$\frac{A.V_t.V_{max}(2I_{max} - I_{sc})}{[V_{max}.I_{sc} + V_{oc}.(I_{max} - I_{sc})].(V_{max} - I_{max}.R_s) - AV_t([V_{max}.I_{sc} - V_{oc}.I_{max})} = e^{\frac{V_{max} + I_{max} R_s - V_{oc}}{AV_t}} \quad \textbf{(3.23)}$$

The shunt resistance is determined by the following equation:

$$R_{sh} = \frac{(V_{max} - I_{max}.R_s)[V_{max} - R_s(I_{sc} - I_{max}) - A.V_t]}{(V_{max} - I_{max}.R_s)(I_{sc} - I_{max}) - A.V_t.I_{max}} \quad \textbf{(3.24)}$$

The saturation current is found as follow:

$$I_0 = I_{0,ref} . \left(\frac{T}{T_{ref}}\right)^3 . e^{\frac{q.E_{g0}.\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)}{A.k}} \quad \textbf{(3.25)}$$

where $I_{0,ref}$ is expressed by the equation below:

$$I_{O,ref} = \frac{I_{SC}}{e^{\frac{V_{OC}}{AV_t}} - 1} \quad \textbf{(3.26)}$$

The photo current is calculated using the following expression:

$$I_{pv} = \left[I_0 + k_i . \left(T - T_{ref}\right)\right] . \frac{G}{G_{ref}} \quad \textbf{(3.27)}$$

The cell temperature depends on the solar irradiance and the ambient temperature. An expression using the TNOCT is presented:

$$T_{cell} = T_a + \frac{T_{noct} - 20}{800} G \quad \textbf{(3.28)}$$

3.3 PV/T System Modelling

To analyze the performance of PV/T system shown in Fig. 3.3, an energy analysis is conducted, from which the electrical and thermal efficiencies are determined.

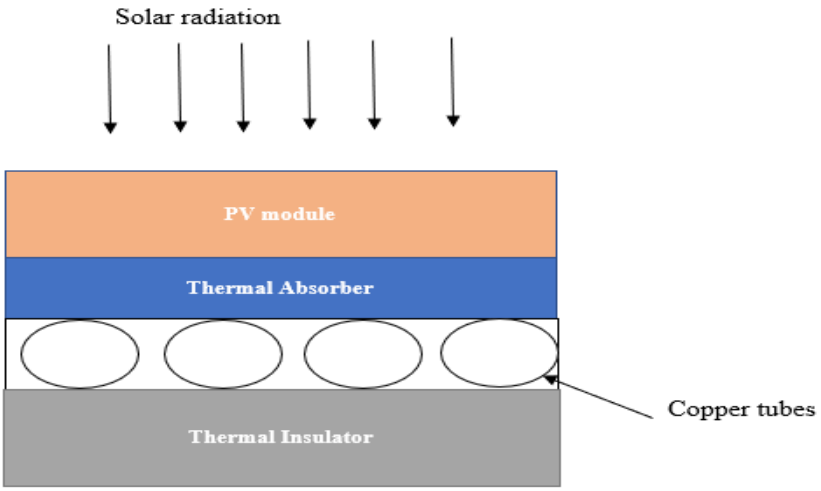


Figure 3.3 Schematic of PV/T system

One of the assumptions done was to consider the PV/T system as a control volume. The absorbed solar irradiance power is calculated as follows:

$$P_{sun} = G A_c \tau_g \alpha_{cell} \quad \textbf{(3.29)}$$

The output useful heat is express as:

$$Q_{th} = m_f C_{p,f} (T_{f,out} - T_{f,in}) \quad \textbf{(3.30)}$$

The output electrical power is determined by this formula:

$$P_{el} = V_{oc} I_{sc} FF \quad \textbf{(3.31)}$$

PV/T system can be classified into two types according to the cooling process: passive and active. Therefore, the electrical efficiency of these systems is different. For a passive system, the electrical efficiency is found as follows:

$$n_{el} = \frac{P_{el}}{P_{sun}} \quad \textbf{(3.32)}$$

In active system, there is an extra component (pump). The electrical efficiency is expressed as follows:

$$n_{el} = \frac{P_{el} - P_p}{P_{sun}} \quad \textbf{(3.33)}$$

where P_p is the power consumed by the Pump

$$P_p = \frac{m_f \Delta P}{\rho_f n_p} \quad \textbf{(3.34)}$$

Another expression of the electrical efficiency is expressed as function of the temperature:

$$n_{PV} = n_r[1 - \beta(T_{cell} - T_r)] \quad \textbf{(3.35)}$$

$$n_{el} = PF n_{PV} \quad \textbf{(3.36)}$$

In a solar collector, the incident solar irradiance is divided into three parts: useful energy gain, thermal losses, and optical losses. The useful gain energy Q_u of the collector is expressed as the difference between the absorbed solar irradiance and the heat loss from the collector [32].

$$Q_u = A_c F_R[G - U_L(T_i - T_a)] \quad \textbf{(3.37)}$$

Where U_L represents the heat transfer coefficient, F_R is the heat removal Factor of the collector and it can be calculated as follows [32]:

$$F_R = \frac{\dot{m} C_p}{A_c U_L}[1 - \exp -(\frac{A_C U_L F'}{\dot{m} C_p})] \quad \textbf{(3.38)}$$

With F' represents the collector efficiency factor and it is determined by the equation below:

$$F' = \frac{1}{\frac{WU_L}{\pi Dih} + \frac{W}{Do+(W-Do)F} + \frac{U_L}{Wh_{pva}}} \quad \textbf{(3.39)}$$

F is a function of the standard fin efficiency, and it is expressed by the equation below[32]:

$$F = \frac{\tanh[m(W-Do)/2]}{m(W-Do)/2} \quad \textbf{(3.40)}$$

where m is defined by:

$$m = \sqrt{\frac{U_L}{kL}} \quad \textbf{(3.41)}$$

Where $k\ and\ L$ are the thermal conductivity and thickness of the absorber plate.

The collector total loss coefficient U_L is the summation of the top, edge and bottom loss, while Q_{loss} is the total heat loss from the collector. They are determined as follow [32]:

$$Q_{loss} = A_C U_L (T_{Pm} - T_a) \quad \textbf{(3.42)}$$

$$U_L = U_t + U_e + U_b \quad \textbf{(3.43)}$$

Where T_{Pm} is the mean plate absorber temperature, given by [32]:

$$T_{Pm} = T_{f,i} + \left(\frac{Q_u/A_c}{U_L F_R}\right)(1 - F_R) \quad \textbf{(3.44)}$$

The top heat loss is expressed by the following equation:

$$U_t = \left[\frac{N}{\frac{C}{T_{pm}}\left(\frac{T_{pm}-T_a}{N+f}\right)^e} + \frac{1}{h_w}\right]^{-1} + \frac{k(T_{pm}+T_a)(T_{pm}^2+T_a^2)}{(\varepsilon_p+0.00591Nh_w)+\frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g}-N} \quad \textbf{(3.45)}$$

ε_p , ε_g, and N are the emissivity of plate, emissivity of the glass and number of glass covers, respectively.

Where h_w is the wind convection coefficient and represents the convection heat loss from a flat plate collector to outside winds.

$$h_w = 5{,}7 + 3{,}8 * V_{wind} \quad \textbf{(3.46)}$$

The equations below are used to calculate C, f, and e :

$$C = 520(1 - 0.000051(\theta)^2) \quad \textbf{(3.47)}$$

$$e = 0.43\left(1 - \frac{100}{T_{pm}}\right) \quad \textbf{(3.48)}$$

$$f = \left(1 + 0.089h_w - 0.1166h_w\varepsilon_p\right).(1 + 0.07866N) \quad \textbf{(3.49)}$$

The bottom lossU_b and edge loss U_e are defined by the following formulas:

$$U_b = \frac{k_i}{L_i} \quad \textbf{(3.50)}$$

$$U_e = \frac{k_{edge}.p.t}{L_{edge}.A_c} \quad \textbf{(3.51)}$$

The edge losses are so small; thus, it can be neglected in some cases for the sake of simplicity.

Another important expression is the output temperature of the fluid, which is given by [32]:

$$T_{f,out} = \left(T_{f,in} - T_a - \frac{G}{U_L}\right) exp\left(-\frac{A_C U_L F\prime}{\dot{m}C_p}\right) + \left(T_a + \frac{G}{U_L}\right) \quad \textbf{(3.52)}$$

The PV cell temperature of the PV/T system can be expressed as follows:

$$T_{cell} = T_a + G\left(\frac{\tau\alpha}{U_L}\right)\left(1 - \frac{n_r}{\tau\alpha}\right) \quad \textbf{(3.53)}$$

The instantaneous thermal efficiency can be calculated as follow[32]:

$$n_{ti} = \frac{Q_u}{GA_c} = F_R(\tau\alpha) - F_R U_L \frac{(T_i - T_a)}{G} \quad \textbf{(3.54)}$$

The expression $F_R(\tau\alpha)$ defines the absorbed energy by the collector, while $F_R U_L$ represents the rate by which energy is lost by the collector.

The total efficiency of the system is calculated as follows:

$$n_{tot} = n_{el} + n_{th} \quad \textbf{(3.55)}$$

3.4 Technical Data For PV/T Simulations

In our study, we are going to use MATLAB software for the simulation of the above equation, a photovoltaic panel and thermal collector which specifications are represented in Table 3.1 and Table 3.2. As this work is done under the climatic conditions of Niamey, data such as ambient temperature and irradiance are collected and used in the simulation. The flow chart of the simulation is presented in Fig. 3.4.

Table 3.1 Specifications of Photovoltaic panel

Size	1480mm*665mm*35mm
Maximum power (Pmax)	150W
Optimum operating voltage (Vmp)	17.2V
Optimum operating current(Imp)	8.72A
Open-circuit voltage(Voc)	21.6V
Short-circuit current(Isc)	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 cell
No. Of cell and connection	36
Weight	13kg

For the thermal collector, the value of the parameters in the table 2 are used for the simulation.

Table 3.2 PV/T collector specifications

Parameters	Symbols	Values	Units
Ambient Temperature	Ta	293	K
emissivity of plate	εp	0.95	-
emissivity of the glass	εc	0.88	-
number of glass covers	N	1	-
Mass flow rate	m	0.07	kg/s
Collector area	Ac	0.98	m^2
Collector circumference	p	4.85	m
Wind speed	V_{wind}	1	m^2/s
PV trans/abs	$(\tau\alpha)$_PV	0.74	-
Absorber thickness	Lab	0.002	m
Thermal conductivity of absorber	Kab	390	W/m.k
PV thickness	Lpv	0.04	m
Thermal conductivity of PV	Kpv	90	W/m.k
Insulator thickness	Li	0.05	M
Thermal conductivity of insulator	Ki	0.045	W/m.k
Edge thickness	Ledge	0.025	M

Table 3.2 (continued) PV/T collector specifications

Tube spacing	W	0.1	M
Tube outer Diameter	Do	0.01	M
Heat transfer coefficient from cell to absorber	h_pva	45	W/m^2 K

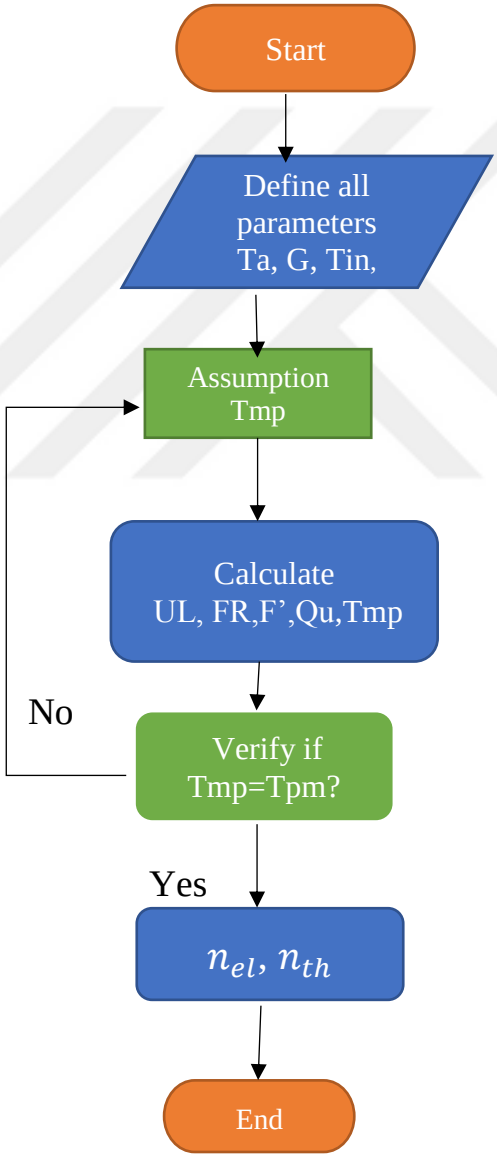


Figure 3.4 Flow chart of the simulation model

CHAPTER 4

RESULTS AND DISCUSSION

The performance of the photovoltaic-thermal system is affected by many factors such as solar irradiance, temperature of the PV cell, absorber plate parameters, and design parameters see Table 3.2. The results obtained are simulated using MATLAB software and weather data of three different months (May, September, and January) of Niamey were utilized in the mathematical model to analyze the performance of PV/T system and PV stand-alone. The irradiance of 7th May was approximated from the daily average received and the study of Maigargue D. et al. [2], and the daily average irradiance values are used for January and September.

The variation of the ambient temperature and solar irradiance of 7th May are presented in Fig. 4.1 , where the temperature varies from 33℃ to 46℃, and the maximum solar irradiance obtained is 970W/m^2. That day was one of the hottest days in Niamey city.

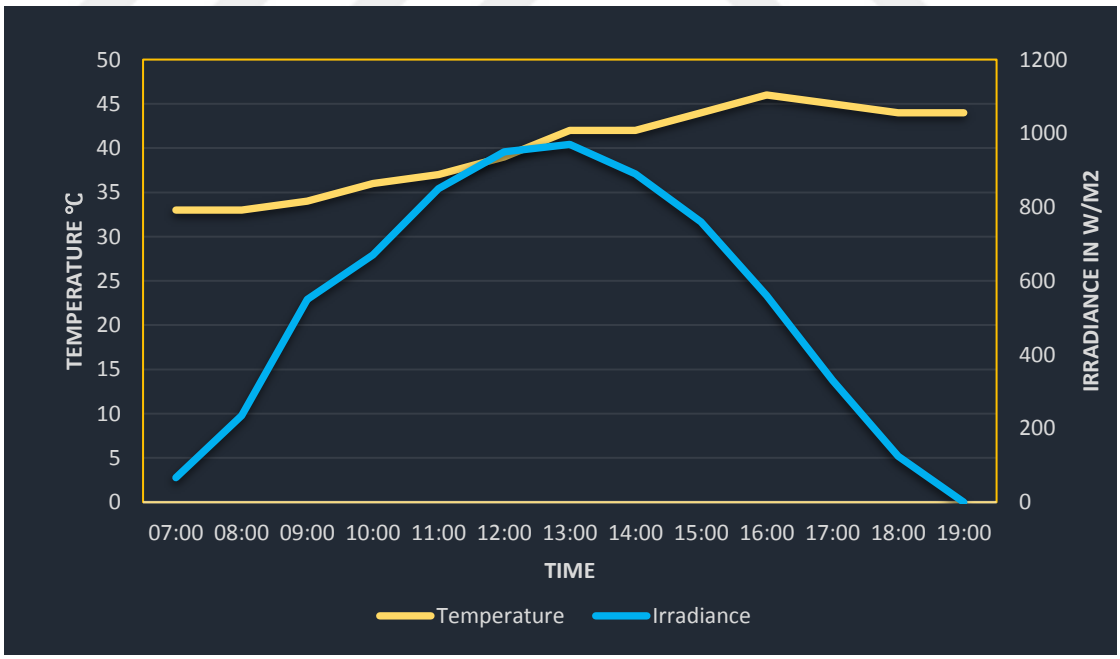


Figure 4.1 Solar irradiance and Ambient temperature of Niamey in 7th May 2019

Fig. 4.2 and Fig. 4.3 represent the daily average ambient temperature and irradiance of September and January, respectively. It can be observed that for these months the temperature is not as high as the previous month, with a significant irradiance. Thus, the maximum irradiance recorded is 1073.86 W/m^2 in January, and 856.25 W/m^2 in September. The highest temperatures in these months were 30.66℃ and 35.04℃.

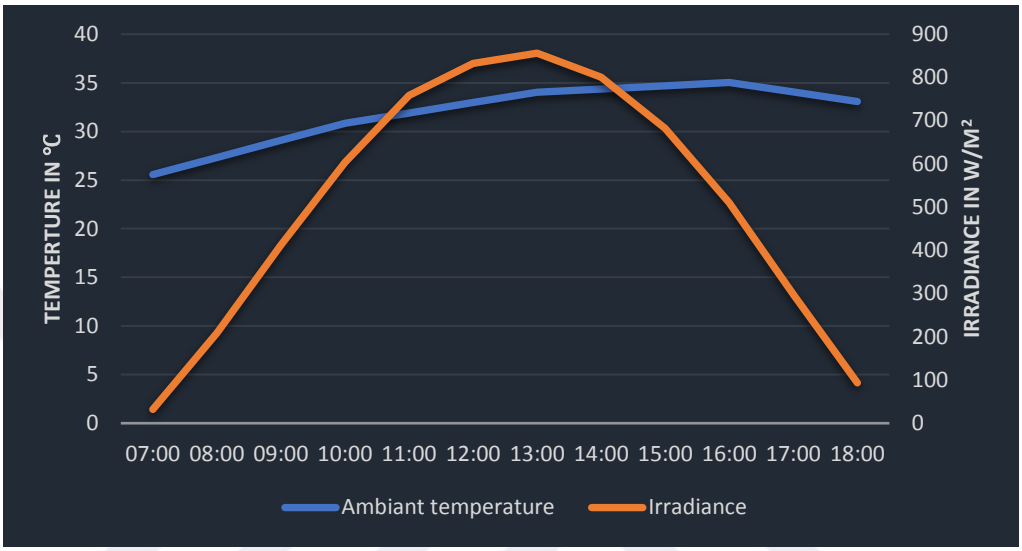


Figure 4.2 Solar irradiance and Ambient temperature of Niamey in September 2019

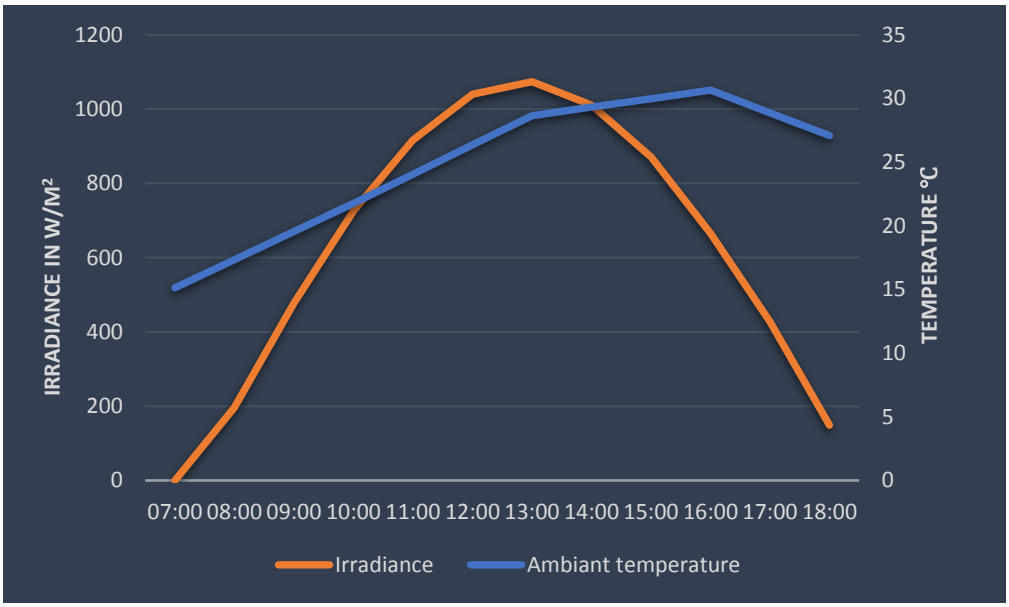


Figure 4.3 Solar irradiance and Ambient temperature of Niamey in January 2019

Figures 4.4 and 4.4 show the I-V curve of uncooled photovoltaic panel and cooled photovoltaic panel for irradiances of 760 W/m^2 and 970 W/m^2. For these irradiances, the cell temperatures of the cooled PV module (53℃ and 56℃) are smaller than the ones of uncooled PV module (67℃ and 71℃). As expected, the increase of the PV module temperature affects mostly Voc which is high for the cooled PV module comparing to the uncooled PV module. While a small affect is observed in short-circuit current (Isc).

For both of panels, the irradiance affected mostly the short-circuit current. Thus, for the given irradiance above , the values of Isc are 7.5A and 9.6 A, respectively.

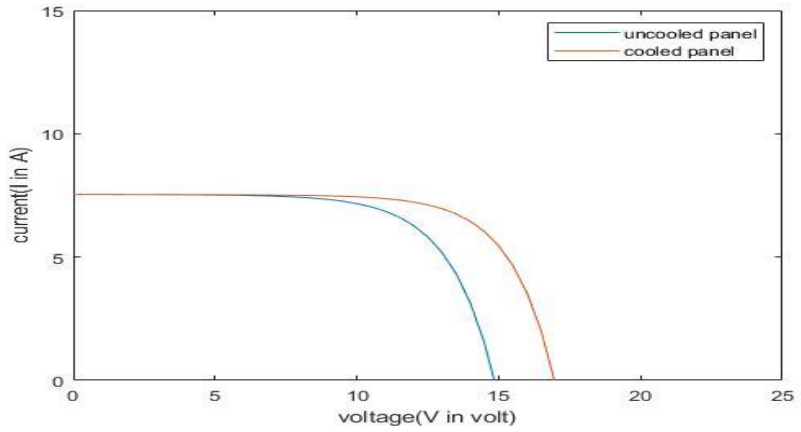


Figure 4.4 I-V curves of cooled and uncooled PV modules at G=760 W/m^2, with module temperature of 53℃ for the cooled PV module and 67℃ for the uncooled PV module

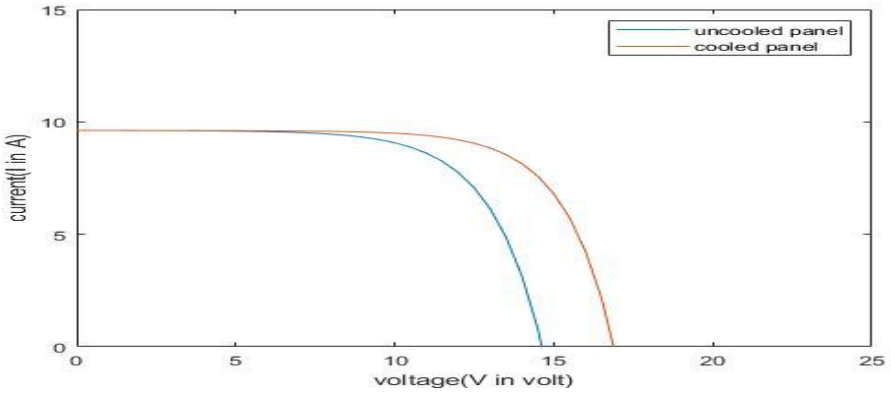


Figure 4.5 I-V curves of cooled and uncooled PV modules at G=970 W/m^2, with module temperature of 56℃ for the cooled PV module, and 71℃ for uncooled PV module

The temperature of PV module and the irradiance affect the electrical power of the module. Thus, the electrical power of the cooled panel is higher than the uncooled PV module. The highest electrical power of the cooled PV panel is 118W recorded at irradiance of 970 W/m^2 with the module temperature equals to 56℃, whereas for the highest electrical power of uncooled PV module is 98W as shown in Figures 4.6 and 4.7.

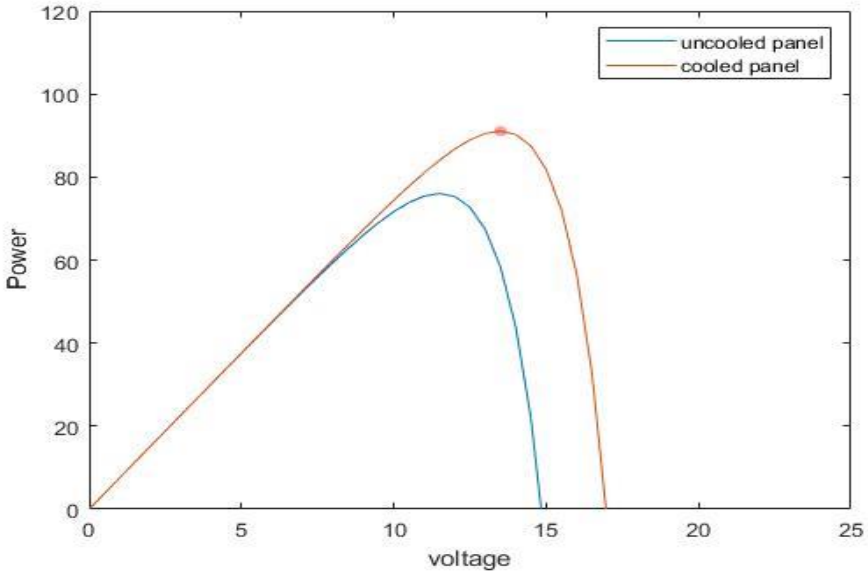


Figure 4.6 P-V Curves of cooled and uncooled PV modules at G=760 W/m^2

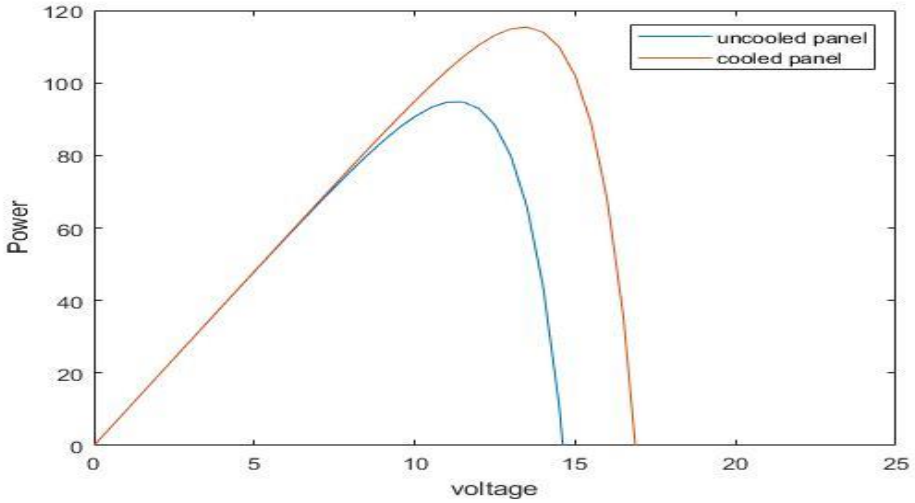


Figure 4.7 P-V Curves of cooled and uncooled PV modules at G=970 W/m^2

One of the factors affecting the performance of the photovoltaic module is temperature. The increase of the temperature clearly affects the efficiency of the PV panel which decreases gradually. Thus, one of reasons of creation of the PV/T systems is the reduction of the module temperature by cooling . Fig. 4.8 presents the cell temperature of two PV panels: cooled and uncooled. As expected, the temperature of the cooled PV panel is found to be smaller than the one of the uncooled panel. At the maximum irradiance (G=970 W/m^2, around noon), the cell temperature of the PV module was measured, it was 71.73℃,whereas the cell temperature of the PV module in the PV/T system was 56℃. The temperature of the PV module in the PV/T system decreased by 15℃.

The variation of the cell temperature of PV and PV/T modules in January and September are presented in Fig. 4.9 and Fig. 4.10. In January, a reduction of about 12℃of the cell temperature is observed. The maximum cell temperature of the PV and PV/T modules is 64.89℃ and 47.01℃, respectively. A decrease of cell temperature is also recorded in September. Thus, the highest temperature of both of panels is 48.5℃ for PV/T module and 62.93℃ for PV stand-alone. By consequent, the cell temperature reduces approximately by13℃.

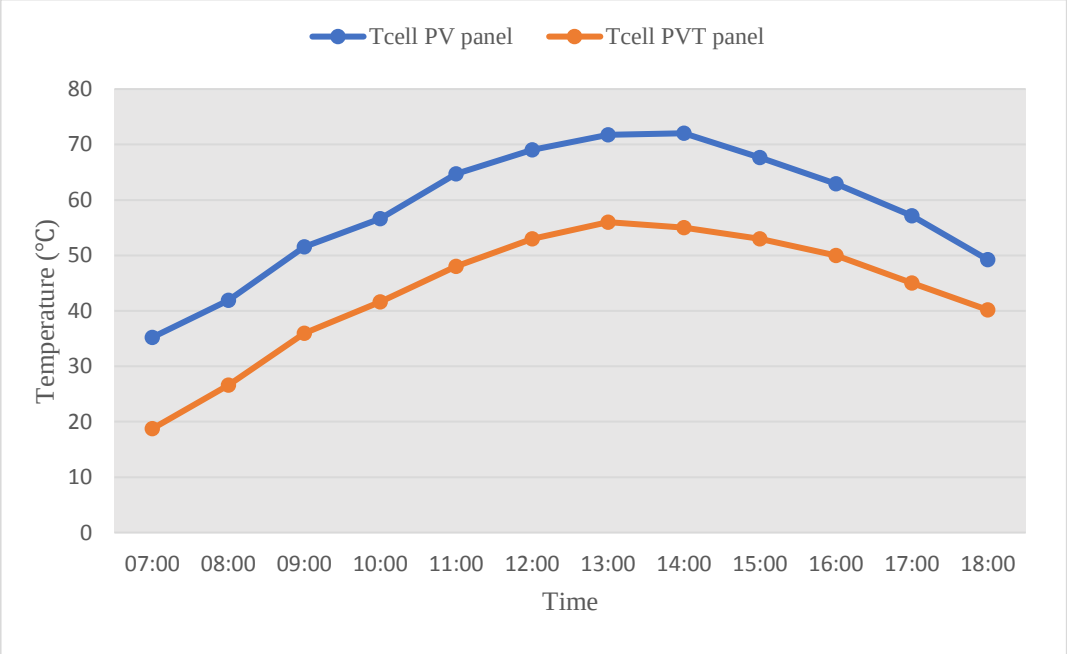


Figure 4.8 Comparison of the cell temperature of the PV and PV/T systems in May 2019

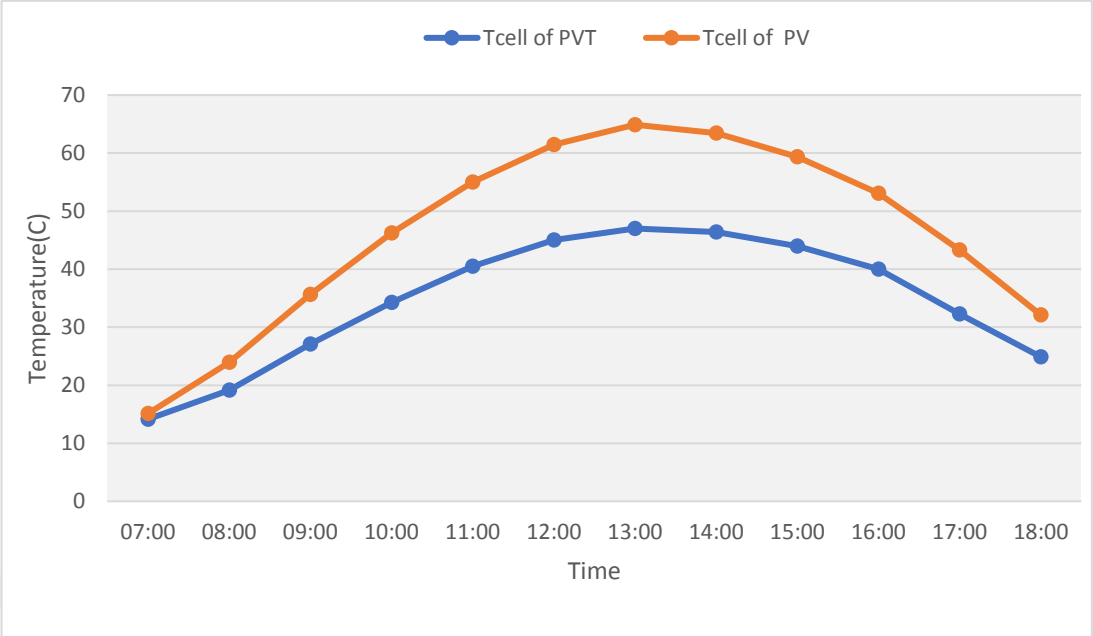


Figure 4.9 Comparison of the cell temperature of the PV and PV/T systems in Janaury 2019

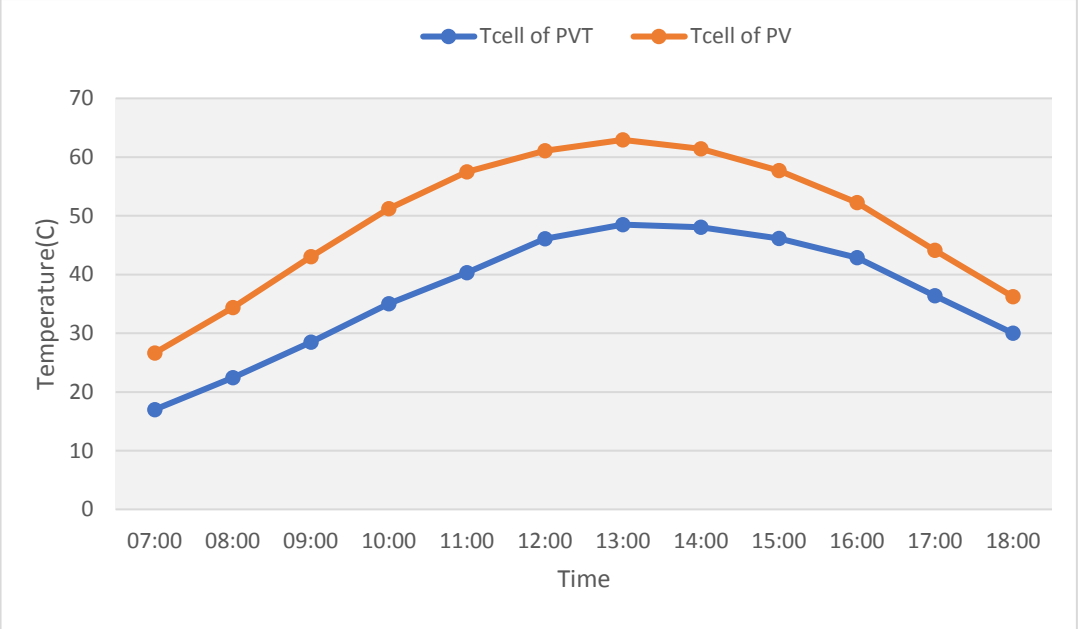


Figure 4.10 Comparison of the cell temperature of the PV and PV/T systems in September 2019

As stated earlier, the cell temperature plays a primordial role in the performance of the photovoltaic systems . The increase of the cell temperature leads to the decrease of the electrical efficiency of the PV stand-alone and PV/T system. By consequent, the smaller the cell temperature is, the higher the electrical efficiency, and as it is shown

in Fig. 4.11, the cell temperature of PV module in PV/T system is smaller than the one of PV module stand-alone. Therefore, the electrical efficiency of PV/T system is greater than the electrical efficiency of PV system as shown in Fig. 4.7. The electrical efficiency of PV module increases from 12% to 13.64% at the maximum irradiance.

The effect of cell temperature on the electrical efficiency in cold weather is demonstrated in Fig. 4.12 and Fig. 4.13. For the month of January, the electrical efficiency improved from 12.81% to 14.30% at maximum irradiance. While in September, the electrical efficiency enhanced from 12.7% to 14.12% at noon time. As predicted, the cell temperature is indeed a significant factor affecting the performance of PV system.

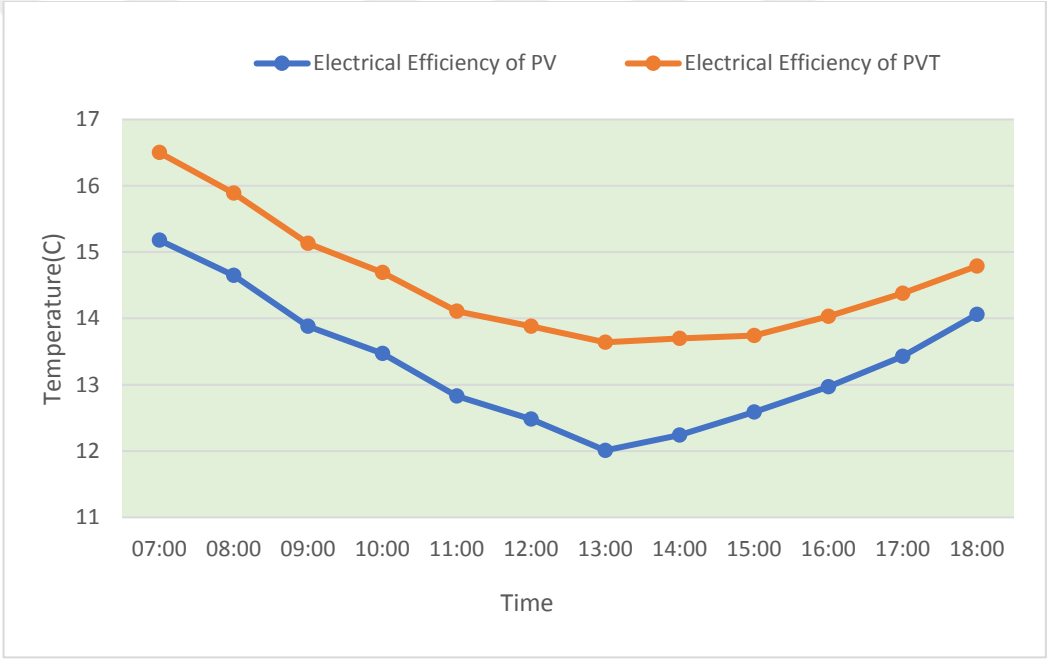


Figure 4.11 Comparison of electrical efficiency of PV and PV/T systems in May 2019

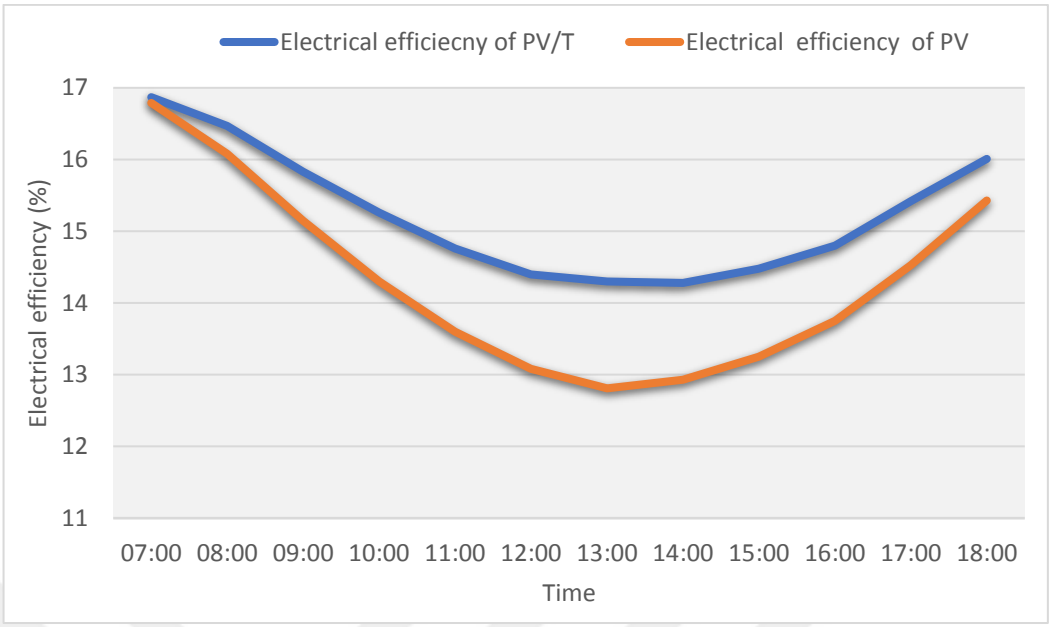


Figure 4.12 Comparison of electrical efficiency of PV and PV/T systems in January 2019

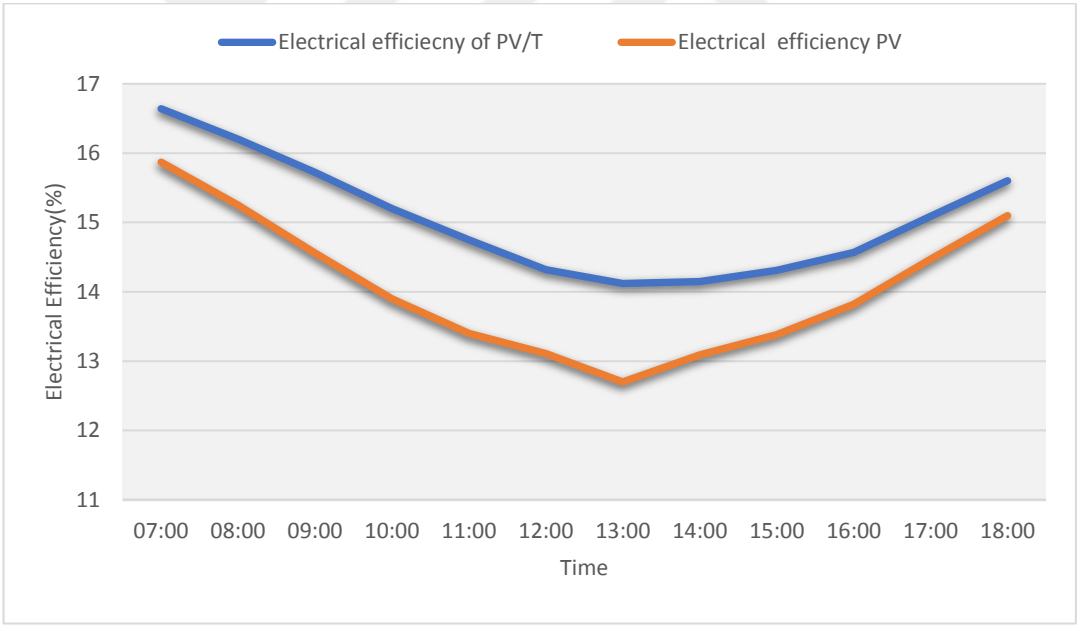


Figure 4.13 Comparison of electrical efficiency of PV and PV/T systems in September 2019

PV/T systems are known for their dual benefits: enhancing the electrical efficiency of PV module and generating useful heat, is indeed affected by many parameters, the irradiance in particularly. As it is shown in Fig. 4.14, the increase of the useful heat is

proportional to irradiance. The maximum value of useful heat is 648.27 W, obtained at noon at G=970 W/m^2.

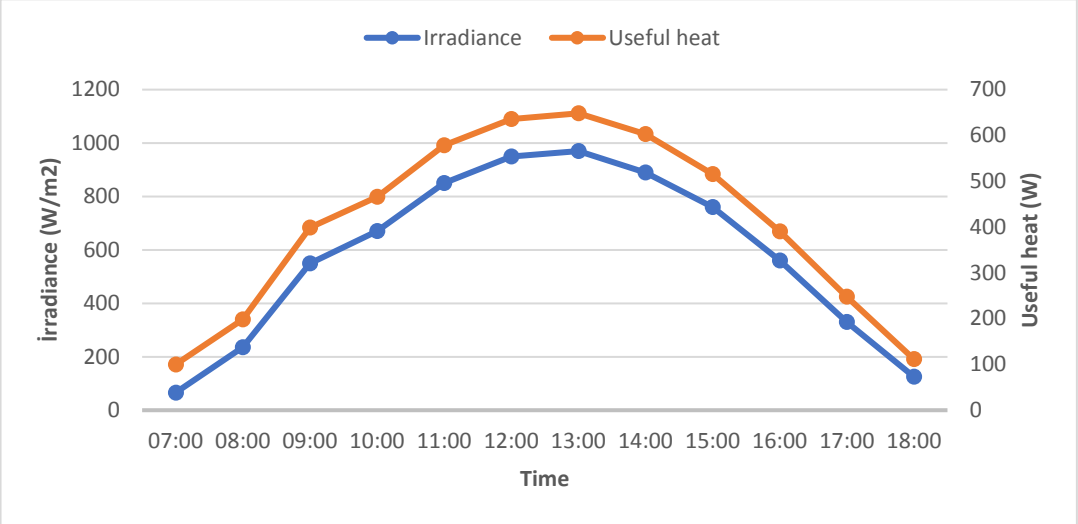


Figure 4.14 Effect of irradiance on the useful heat in May 2019

Fig. 4.15 presents the hourly variation of heat gain in January and September. As the heat gain increases with the increase of the irradiance, the maximum heat gain is recorded in January with 724.14 W at an irradiance of 1073.86 W/m^2. The highest heat gain obtained in september is 576.41 W at 856.25 W/m^2. For both of months, the heat gain is low at sunrise and sunset.

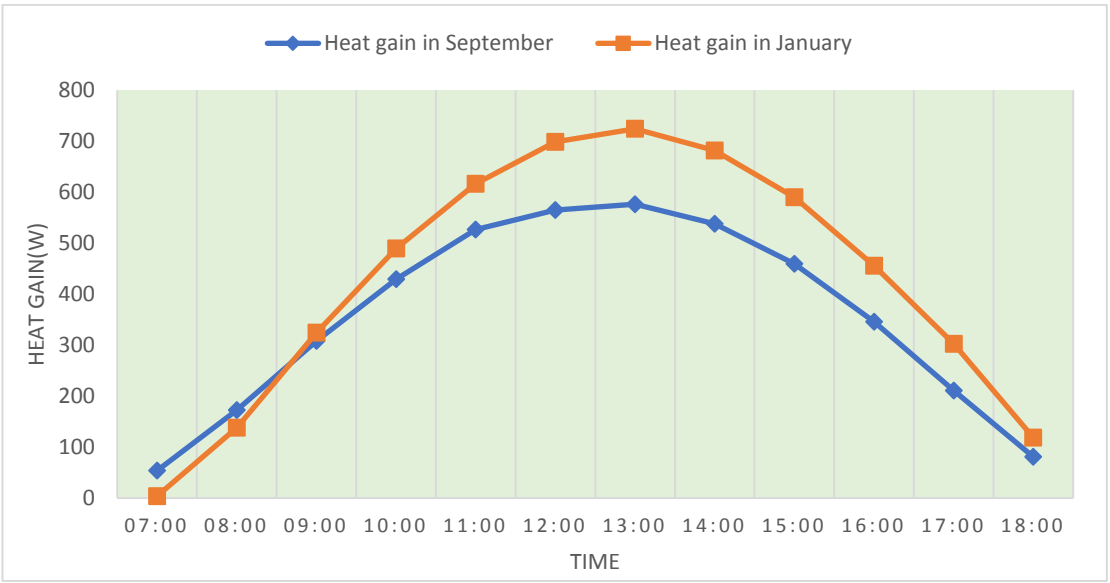


Figure 4.15 The variation of useful heat in January and September 2019

The thermal efficiency is influenced by many factors such as solar radiation intensity, ambient temperature, inlet and output temperature. The variation of the outlet and inlet water temperature is shown in Fig.4.18. The variation of the thermal efficiency with respect to the irradiance is shown in Fig. 4.16 in May 2019. Unlike the useful heat, the thermal efficiency decreases with the increase of the irradiance. The thermal efficiency was in range of 85% at 7 A.M to 66.69% at 1 P.M, and 67.41% at 2 P.M to 78% at 6 P.M.

In January, the thermal efficiency is varies from 70.17 % at 8 A.M to 67.17% at noon, then increases gradually till 70.7 % at 6 P.M see Fig. 4.17. The average thermal efficiency is found to be 69.24%. The thermal efficiecny in September decreases from 82.62 % at 8 A.M to 67.32 at 1 P.M, and increases until 83%. The average thermal efficiecny of 72 % is obtained.

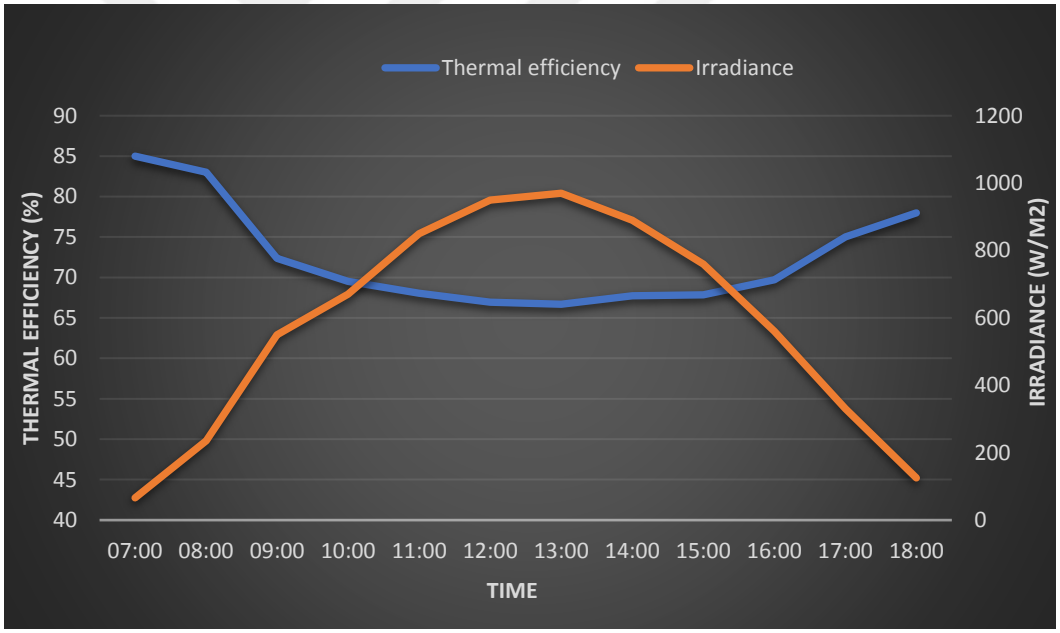


Figure 4.16 Variation of thermal efficiency and solar radiation in May 2019

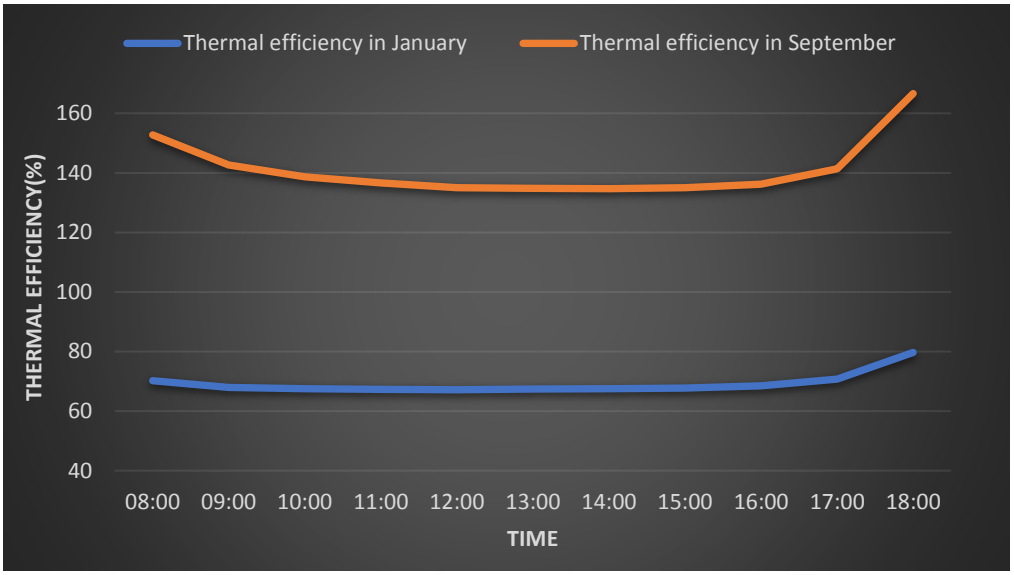


Figure 4.17 Variation of thermal efficiency and solar radiation January and September 2019

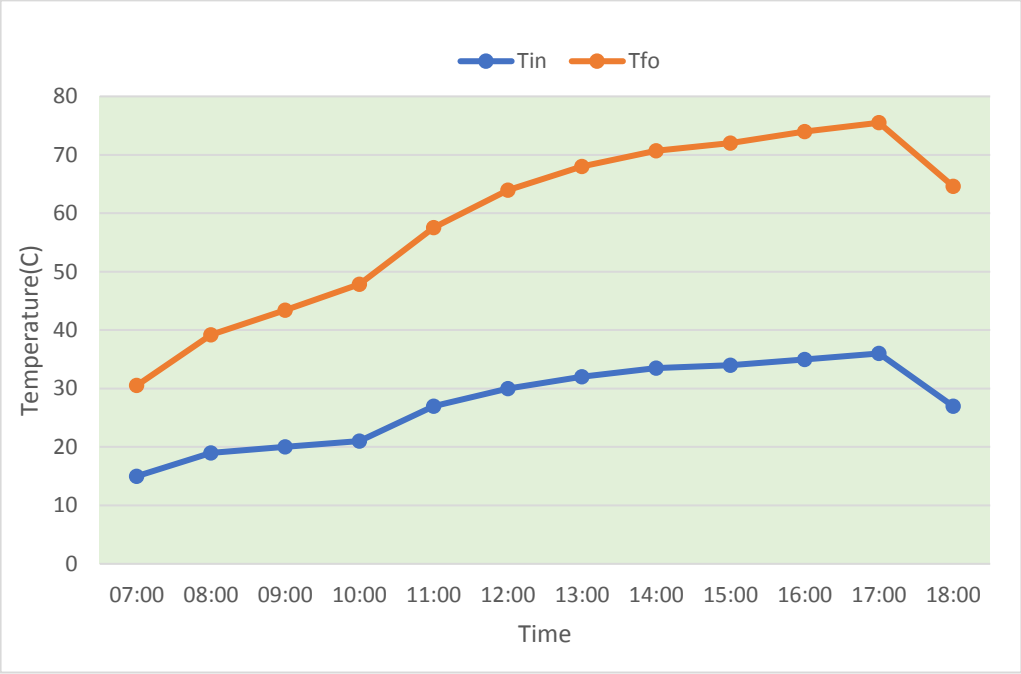


Figure 4.18 Variation of inlet temperature and output temperature of May 2019

The obtained thermal energy is transfered to the water, as result the water temperature increases. Fig. 4.19 and Fig. 4.20 represents the variation of the outlet and inlet water temperature in January and September.

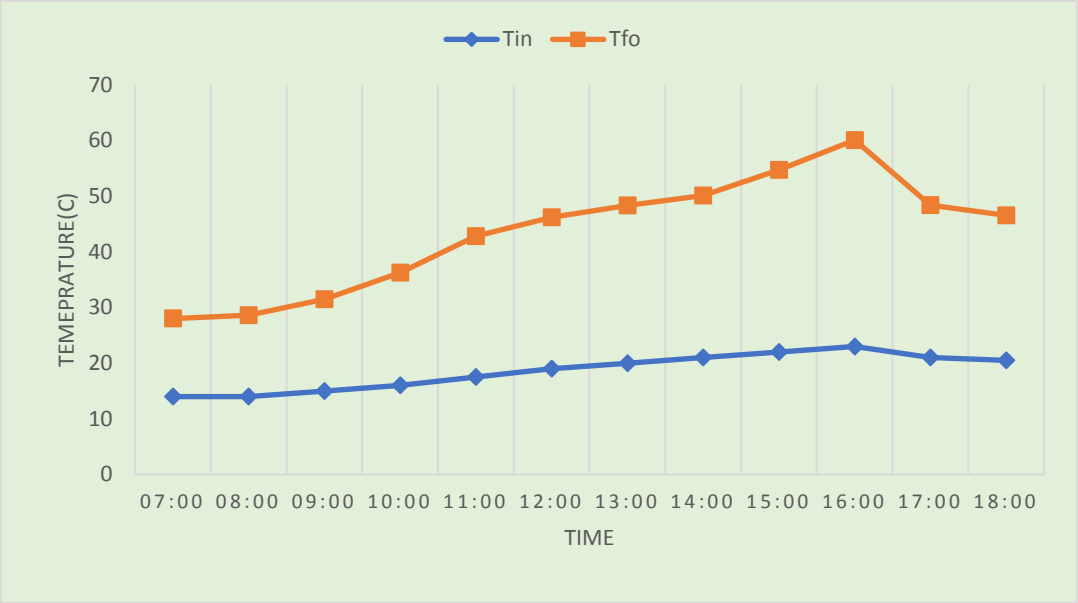


Figure 4.19 Variation of inlet temperature and output temperature in January 2019

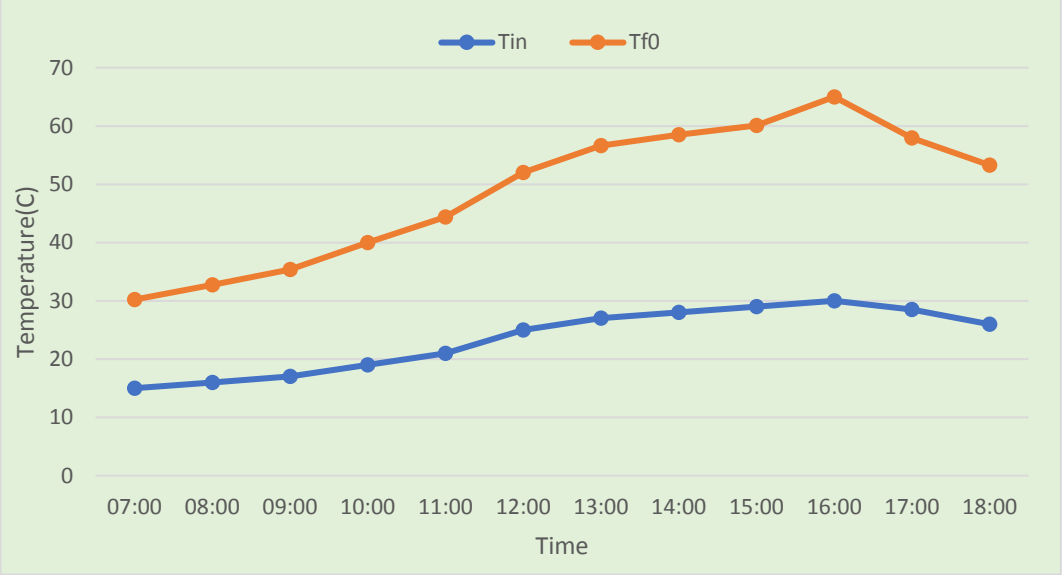


Figure 4.20 Variation of inlet temperature and output temperature in September 2019

Fig. 4.21 shows the variation of the electrical power of PV and PV/T modules with time. As predicted, PV/T system generates more electrical power compared to PV module. At maximum irradiance, it is notified that the maximum electrical power generated by PV/T and PV modules are 135 W and 114.07 W, respectively.

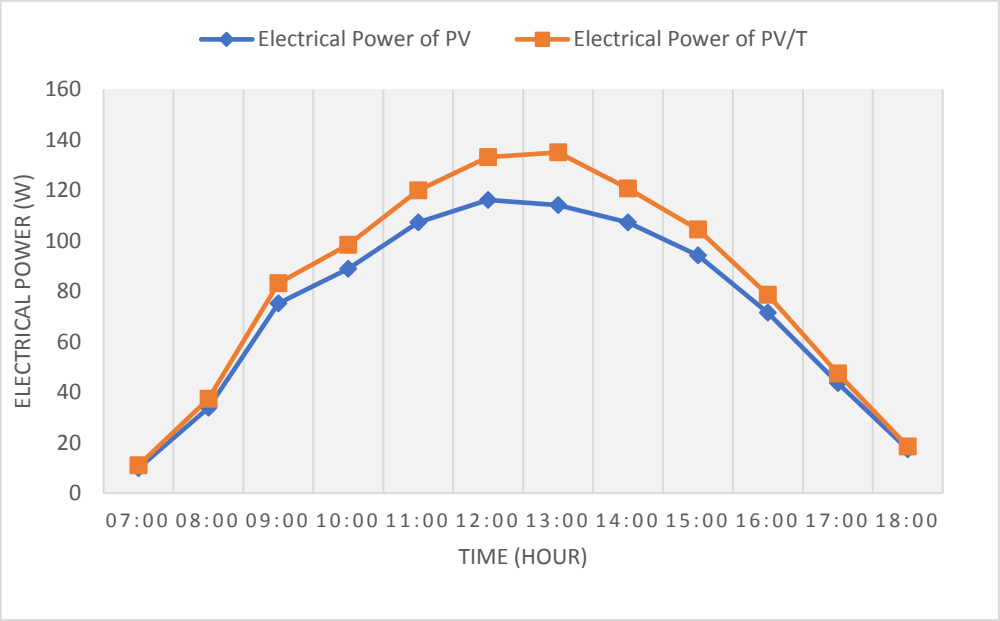


Figure 4.21 Comparison of electrical power of PV and PV/T systems in May 2019

The variation of electrical power of PV and PV/T modules in January and September are given in Fig. 4.22 and Fig. 4.23. During these months, the electrical power of PV/T module increases by 20 W compared to that of PV module in January, whereas in September an increase of about 12 W is observed in the electrical power of PV/T module.

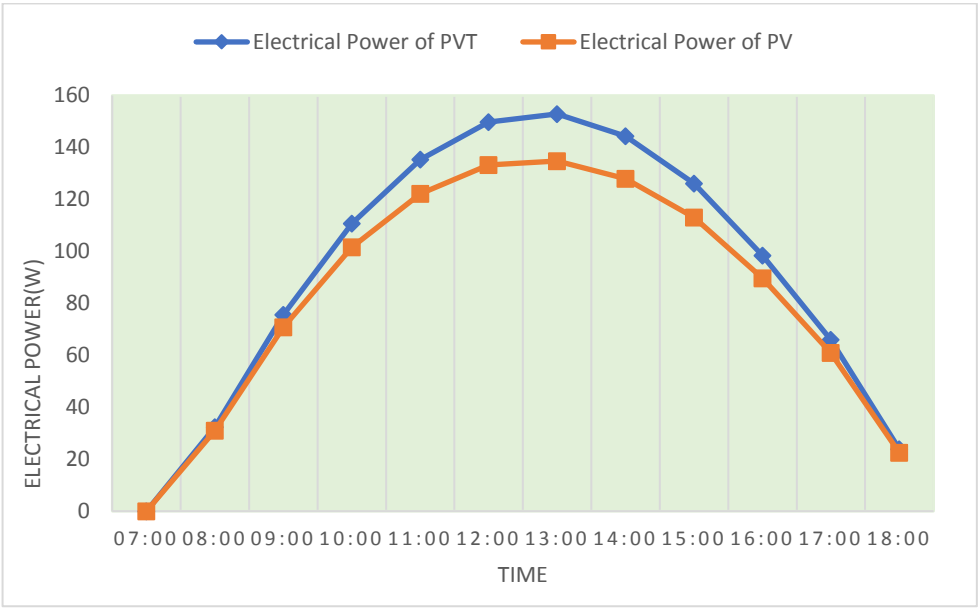


Figure 4.22 Comparison of electrical power of PV and PV/T systems in January 2019

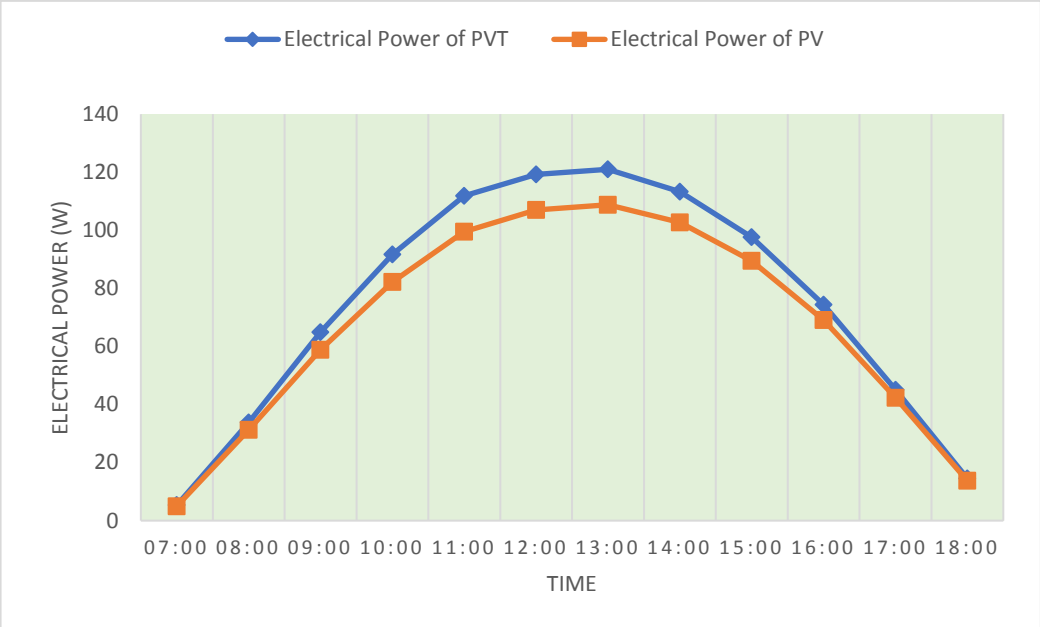


Figure 4.23 Comparison of electrical power of PV and PV/T systems in September 2019

From Table 4.1, it can be observed that the current study is in agreement with the previous works, where a comparison is made with some works from the literature review.

Table 4.1 Performance assessment of present research with previous studies

Author names	Collectors type	Electrical Efficiency	Thermal Efficiency
Hossain et al. (experimental study)	Parallel serpentine flow-based PV/T system	10.46%	76.56%
Hajji et al. (theoretical study)	PV/T hybrid water system	14%	N/A
Ozgoren et al. (experimental study)	PV/T water system	13.6%	51%
The Present work (theoretical study)	PV/T water system	13.64%	66.69%

CHAPTER 5

CONCLUSION

Hybrid Photovoltaic/ Thermal systems also called PV/T systems or solar cogeneration systems are power generation technologies that convert solar radiation into usable thermal and electrical energy. Such systems combine a solar cell, which convert sunlight into electricity, with a solar thermal collector, which captures the remaining energy and removes waste from PV module. By consequent, the electrical efficiency of PV module increases. PV/T systems have a greater overall performance than the PV systems and Solar thermal systems separately. Many studies are conducted on these systems in many countries, but this study is the first one to be done in Niamey city in Niger. Niger is in west Africa and presents an enormous potential in solar energy which can be exploited to meet the energy demand of its population.

The objective of our work was to analyze the performance of the photovoltaic thermal system under the climatic conditions of Niamey. The performance of the PV/T system has been successfully determined in a theoretical study conducted in MATLAB. PV/T cell temperature, electrical and thermal efficiencies, fluid inlet and outlet temperatures were calculated. The PV/T hybrid system efficiency was compared to a solar module. The electrical efficiency of the PV/T system increases by 0.1% /℃ compared to the electrical efficiency of PV stand-alone. Also, the cell temperature of the PV module in the PV/T system decreased by 15 ℃ on 7th May 2019. At noon, the useful heat and the instantaneous thermal efficiency of the PV/T system were recorded to be 648.27 W, and 66.69 % respectively. The result of our study is congruous with previous works as presented in Table 4.1 and shown that PV/T systems can be used in Niger, providing good performance.

In future, experimental study should be done on the PV/T systems under the climatic conditions of Niamey with a variation of the mass flow rate. Also, the performance of the PV/T systems in this city using different coolants such as PCM(phase change material) , nanofluids should be investigated. Other researches can be conducted on the applications of the PV/T systems in other fields such as desalination of water in

rural area of Niger, space heating or cooling, drying for agriculture. Moreover, most of studies were conducted using silicon PV cell, other type of PV cell shall be investigated.

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01-07-2016	30-07-2016	Turkey-Ankara	ARÇELİK	Electronic	Internship	Controlling the electronic devices

TOPICS OF INTEREST

- Solar energy
- Energy systems
- Renewable energy, Solar thermal
- Microprocessors

Department of Energy Systems Engineering

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June 2020
ANKARA