An-Najah National University

Faculty of Graduate Studies

Performance Improvement of Solar PV Modules by Cooling System and the Economic Feasibility of Applying it on large PV Power Plants

By

Ahmad Odeh

Supervisor

Prof. Dr. Marwan M. Mahmoud

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This these was defended successfully on 1/3/2018 and approved by:

Defense Committee Members	**Signature**
Prof. Dr. Marwan M. Mahmoud/ Supervisor	**………….……….…..**
Dr. Mahmoud Salah/ External Examiner	**………………………**
Dr. Imad Ibrik / Internal Examiner	**……………………….**

Dedication

يقول الله سبحانه وتعالى: ﴿هو أنشأكم من الأرض واستعمركم فيها – هود، آية 61﴾

From this perspective, I dedicate this humble work to those interested and researchers who are constantly working to build the land and preserve its resources to meet the needs of future generations.

I hope that this work will be useful.

Acknowledgment

Before all, thank God for the blessing and helping to finish this humble work.

And, many thanks to my parents (Adebah Hamad and Sulieman Odeh) for all the care and support.

Certainly, I would like to thank my supervisor (Prof. Dr. Marwan M. Mahmoud) for all the guidance, experience and valuable advice that contributed to the completion of this work.

Finally thanks to all my friends.

الإقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

Performance Improvement of Solar PV Modules by Cooling System and the Economic Feasibility of Applying it on large PV Power Plants.

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The work provided in this theses, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degrees or certifications.

Student's Name: **أسم الطالب:**

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Performance Improvement of Solar PV Modules by Cooling System and the Economic Feasibility of applying it on Large PV Power Plants

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Prof. Dr. Marwan M. Mahmoud

Abstract

It is known that the temperature of the photovoltaic cell has a remarkable effect on its efficiency. This study measures this effect and tries to prove that cooling of PV systems could be feasible.

Increasing the cell temperature causes some modifications in the characteristics of the semiconductor material (usually silicon) used to manufacture the PV cell, this leads to the decrement in the open circuit voltage of the cell, so decrement in its efficiency.

Based on measurements taken from an installed PV system in Palestine, it is found that the cell temperature could reach 70℃, under normal operating conditions, which is about 3 times higher than the STC operating temperature of the PV cells. This high operating temperature causes about 5% losses in efficiency of a PV system installed in the same area.

A PV module is placed under Palestine climate conditions, by simulation, to simulate the performance during a year at different operating cell temperatures. Cooling the PV module and maintaining its temperature under 30 ℃ will save about 5 volts decrement in the open circuit voltage, and about 5% loses in the total yearly efficiency, which could be lost when operating

the PV module without cooling under normal operating conditions in Palestine.

Applying a cooling system on a certain PV system could be feasible like the one considered in this study as a study case, with a payback period of 4 years the installing of cooling system can be considered feasible.

Because of the cell temperature in the concentrator technology could reaches about 1000°C, the cooling is not an option, and the cells should be cooled to prevent failure.

CHAPTER ONE
INTRODUCTION

General Background:

Power is the most important word in the world over all centuries; people – over all centuries – keep looking for new and continuous sources of power. Sun is the sole source of energy (so of Power) in this planet, therefore we must take advantage of this sole source well.

It is known that the non-renewable energy sources will not stand for a long time, and the day of disappearing of these sources become closer; so sustainability becomes the hot global issue in this century, which means the ability to meet the needs of present generations without compromising the ability of future generations to meet their own needs. Therefore the exploitation of the renewable energy sources become a must.

In about 1954 Photovoltaic technology was born, and the first silicon Photovoltaic (PV) cell was appeared; and generating electricity from sun light was started; but from that day until now, the most important and challenging topic is the efficiency of these PV cells.

Low efficiency of PV modules is the biggest problem in using these modules to generate electricity from sun light this efficiency doesn’t exceeds 20% in the best conditions [1]. But the biggest challenge here is to keep this efficiency at its maximum or optimum value, as it depends on different factors.

Actually, the actual efficiency of photovoltaic modules is often lower than the predicted efficiency by standard test conditions (STC) or by standard operating conditions (SOC), because these standard conditions is very hard to be achieved in real applications.

Importance of the study:

As mentioned above, keeping the efficiency of PV modules at its maximum or optimum value is a big challenge, in other words, achieving the standard conditions in real applications to get the predicted efficiency.

This study try to find out how to keep this performance as high as possible by using cooling system to cool the PV modules, and whether using such cooling system is economical feasible or not.

Objectives of the study

The objectives of this thesis are referred to the followings:

- **The overall goal:**

Improving the performance of the PV modules by using cooling system, and determining the economic feasibility of this improvement when applying this method on a study case.

1. Investigating the previous literatures about cooling of PV modules and the effect of cooling on the overall efficiency.
2. Reducing the energy production cost by improving the overall performance of the PV module, then less number of modules and area needed for a certain capacity [1, 2, 3, 4].
3. Trying to define the best and most efficient cooling method which can achieve the maximum possible improvement with the lowest cost [2, 3].

Thesis Organization:

The following chapters summarize the work done in this thesis:

Introduction:

The actual efficiency of photovoltaic modules is often lower than predicted by standard test conditions (STC) or standard operating conditions (SOC). The energy yield of photovoltaic (PV) modules depends on a large number of factors.

The most important two factors are the amount of solar radiation energy that strikes the plane of the PV modules, which in turn depends on the local climatic conditions. These local conditions can be modified by the mounting approach, e.g. fixed or tracking, inclination angle, building integration, etc. [1].

According to the solar radiation factor, improving the performance of PV modules is based on increasing the intensity of the falling radiation on the PV cells surface, which can be achieved - commonly- by using concentrators, lens and/or tracking systems. The principle of these techniques is to achieve the maximum solar intensity on the PV panel by decreasing the incident angel. But the problem associated with these techniques is the increase in PV cell temperature above the operating limit which results in reducing the cell efficiency and probably leads to cell damage in case of overheating. So, the PV modules will be more efficient when exposed to cooling process especially during hot weather [1].

The second important factor is the temperature of the PV module which in turn depends on the ambient (air) temperature, the solar irradiance, the type of mounting, and cooling by natural wind or by a cooling system.

It is known that, we couldn’t control the air temperature and the radiation intensity (actually – as discussed above- in installing PV systems we usually try to get the maximum irradiance in order to increase the generated power. This increases the cell or module temperature which decreases the performance of the module). The mounting type of the modules sometimes is strict and we cannot modify it as required because of the problems of space fixed construction. Then the only way to decrease the temperature of the PV modules is by cooling them by the natural air or by using a special cooling system in order to maintain the minimum possible temperature (as close as possible to the STC temperature (20 – 25) ˚C) at the maximum available radiation especially at peak sun hours [1,2].

Cooling of PV panels can be considered as the less expensive technique that is used to improve the PV panel performance. There are different methods for cooling the PV modules. First, good ventilation between modules by mounting them in certain way. A second method is by cooling the back panel of the PV module by water -or other working fluid- flowing in pipes. The third method by cooling the front panel of the module by water. Each method of these has its advantages and disadvantages, and they affect the performance of the PV module in different ways and percentages [3].

CHAPTER TWO
LITERATURE REVIEW

2.1. Previous Studies

Improving the PV performance by cooling, to minimize the effect of cell temperature on the performance, has been discussed by numerous publications. Several researches and studies have been conducted to study this issue.

A paper published by S.Odeh, and M. Behnia discussed cooling of PV modules using water [3], this study used a special technique for cooling the PV modules by comprising water flowing on the upper surface of the PV module. Multi crystal photovoltaic module of 60 W maximum power was used, with different inclination angels (including the horizontal position). The operating cell temperature was measured at constant radiation. The water used for cooling is at ambient temperature which is always lower than the cell operating temperature.

In this study Odeh and Behnia concluded that cooling the PV module by this technique will decrease the cell operating temperature by about 26 C° at radiation 1000 $W/m^{2.}$

Other interesting result in this study, which is increasing the radiation intensity on the cell. As they stated that the refraction of the solar beam in water layer at the upper surface of the PV module will increase the incident radiation on the cells. But they did not prove this result by any measurements or resources.

Finally the study found that, cooling the PV module by using the technique of flowing water on the upper surface will increase the system output in the range of 4-10%. Part of this increase (50%) is due to cooling by direct contact between water and PV module surface; the other part is due to refraction of the solar beam in water layer and the increase in incident radiation.

Another study conducted by H.G Teo, P.S Lee, and M.N.A. Hawlader discussed cooling the PV cells by air [4]. Photovoltaic/thermal solar system was designed and uniform airflow distribution was used to cool the PV cells. They suggested to attach a parallel array of ducts with inlet/outlet manifold for uniform distribution of airflow to the back of the PV panel.

The results were taken for both situations, with an active cooling and without cooling. They found that the operating temperature of the PV module without cooling can reach about 68 C° and the electrical efficiency dropped significantly o about 8.6%. By using the attached cooling system, the operating temperature of the module could be maintained at 38 °C, and the electrical efficiency could also be kept at around 12.5%, which is higher than using the module without cooling by about 3.9%. This increase in efficiency cannot be ignored in solar systems, and it can make a remarkable difference in the output of the system.

In this study, the air flow which is sufficient to absorb the maximum amount of heat from the PV panel was calculated As if this flowrate is exceeded the thermal and electrical energies are no longer affected.

Other study conducted by J.K. Tonui and Y. Tripanagnostopoulos, which focused on the possibility of getting benefit from both electricity and heat energy from a commercial PV module.

This study is focusing on exploiting the heat energy gained from the PV module in several applications such as heating, cooling, and for several industrial and agricultural processes.

Two modifications were suggested to be done in this study, the first one is inserting a thin metallic sheet (TMS) between the back side of the arranged PV cells and the back side of PV module. The second modification is to use Fins in the space between the back side of the arranged PV cells and the back side of PV module. The idea of inserting these modifications is to increase the heat transfer area (surface).

Then these two modifications are compared with the reference one which has no modifications (commercial PV). For the two modifications two air flow modes were used. The natural airflow and forced air flow.

As a result of this study, it was found that for forced convection, using Fins is more efficient than TMS, as it yields an efficiency of 30% (rising in temperature of the flowing air), then the TMS with 28%. Last one is the typical (with no modifications) with 25%. (These efficiency values represent the rising in temperature of the flowing air through the channel, and so indicate the decreasing in cell temperature).

Of course using these systems will cool down the PV module, and this will affect the performance of electrical production of PV. In the study the change in electrical efficiency due to the modifications was calculated to be 4% increment.

The result of this study appears that we can use both electrical and thermal energy produced by the PV module, which results in increasing the overall efficiency of PV systems.

CHAPTER THREE
PV CELLS AND TEMPERATURE EFFECT

3.1. Introduction

As known now, the PV technology is used widely around the world, and so on in Palestine. So, it becomes important to study this technology to make it more efficient and more reliable and trustable, and to improve its economic feasibility.

One of several parameters affects the performance of the PV cells is the temperature of the cell (operating temperature). It has a remarkable effect on the output of the PV cell, so on the whole PV system.

In this chapter, temperature effect on PV performance will be discussed in details to find the relation between the temperature of the cell and its performance.

Real measurements in Palestine will be used to study this effect in real cases under natural climate conditions in Palestine. After that a simulation procedure by MATLAB program will be done to simulate the effect of different operating temperatures on the cell performance.

The effect of temperature on different types of PV cells will be discussed.

3.2. Temperature Effect

3.2.1. Theory of temperature effect.

It is known that the temperature of the cell has a remarkable effect on the performance of the cell. The question may appear is how does the temperature affect the performance? How the temperature of the cell changes due to ambient temperature and solar irradiance intensity? What is NOCT,

H_v and H_i? This section will try to explain the theory behind the phenomena of temperature effect.

3.2.2.

3.2.2.1 Nominal operating cell temperature (NOCT)

When operating in the field, PV modules typically operate at higher temperatures. So, in order to determine the power output of the solar cell, it is necessary to determine the expected operating temperature of the PV module.

The Nominal Operating Cell Temperature (NOCT) is defined as the temperature reached by open circuited cells in a module under the conditions as listed below: [6]

1. Irradiance on cell surface = 800 W/m^2
2. Air Temperature = 20°C
3. Wind Velocity = 1 m/s
4. Mounting = open back side

The nominal operating cell temperature provides a measure of how the PV cell temperature (the surface temperature of the PV array) varies with the ambient temperature and solar radiation.

Module design, including module materials and packing density, has a major impact on the NOCT.

NOCT differs from module to another depending on the manufacturer, and manufacturing technology. But in general the typical value of NOCT is between 45 – 48 C° [1].

This value is used to calculate the cell temperature, as it will be discussed later.

3.2.2.2 Temperature coefficients for Power, Voltage and Current (H_P, H_V and H_I).

Each solar cell (or PV module) comes with unique temperature coefficients. These coefficients are important to measure the change of voltage, current and power of PV module due to temperature change.

Temperature coefficient of voltage (H_V): measures the change in open circuit voltage of PV module due to the change in temperature.

Typically, H_V = - 3.7 * 10^{-3} mV/1 C°. [1]

Temperature coefficient of current (H_I): measures the change in short circuit current of PV module due to the change of its temperature.

Typically, H_I = 6.4 * 10^{-4} mA/1 C°. [1]

Temperature coefficient of power (H_p): measures the change in power due to PV temperature change. This coefficient can be estimated using the temperature coefficient of voltage H_V, according to the following equation. [7]

$$H_P = \frac{H_V}{V_{mp}} \tag{3.1}$$

Where:

H_V = the temperature coefficient of the open-circuit voltage [V/°C].

V_{mp} = the voltage at the maximum power point under standard test conditions [V].

Usually the temperature coefficient of voltage is provided with data sheet of the module from the manufacturer as it is the main (and first) affected coefficient due to cell temperature.

3.2.2.3 How temperature affect solar cells

As known, the PV module output in the field differs from that at lab or at STC due to some reasons, mainly due to the cell temperature. But why does the cell temperature increases. And how does it affect the output and so the performance of the PV module?

All semiconductor devices including solar cells are sensitive to temperature. An increase in temperature reduces the band gap of a semiconductor, thereby affecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material. Lower energy is therefore needed to break the bond.

In the bond model of a semiconductor band gap, reduction in the bond energy also reduces the band gap. So increasing the temperature reduces the band gap.

In a solar cell, the most affected parameter by an increase in temperature is the open-circuit voltage. The impact of increasing temperature on open circuit voltage is shown in the figure 3.1.

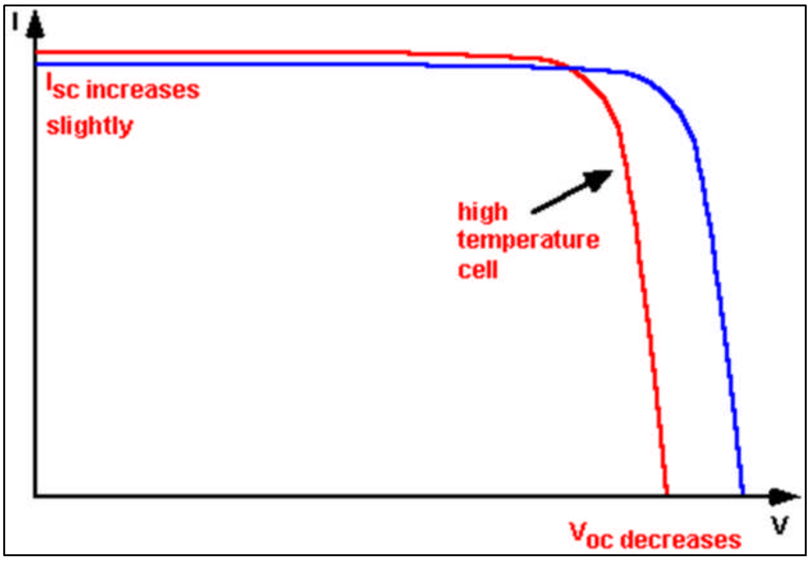


Figure (3.1): The effect of temperature on the IV characteristics of a solar cell.

In equation 3.15, I_0 is the diode current and it is subtracted from the generated current due to radiation, so higher diode current I_0 means higher losses in cell performance.

Also I_0 is one of the parameters that affects the open circuit voltage, and the open circuit voltage decreases as temperature increases, as it is obvious in the following equation [1].

$$V_{oc} = \frac{kT}{q} \ln \frac{I_{sc}}{I_o} \qquad (3.2)$$

The equation of I_O is:

$$I_o = qA \frac{Dn_i^2}{LN_D} \qquad (3.3)$$

Where:

q: electronic charge = 1.602 × $10^{-19.}$

A: is the area.

D: diffusivity of the minority carrier given for silicon.

$N_{D:}$ doping density.

n_i: intrinsic carrier concentration.

In the above equation, many of the parameters have small temperature dependence, but the most significant effect is due to the intrinsic carrier concentration, n_i. The intrinsic carrier concentration depends on the band gap energy (lower band gaps give a higher intrinsic carrier concentration), and on the energy which the carriers have (higher temperatures give higher intrinsic carrier concentrations). The equation for the intrinsic carrier concentration is illustrated hereafter [6]:

$$n_i^2 = 4\left(\frac{2\pi kT}{h^2}\right)^3 (m_2 * m_h)^{3/2} \exp\left(-\frac{E_{Go}}{kT}\right)$$

$$= B\,T^3 \exp\left(-\frac{E_{Go}}{kT}\right) \qquad (3.4)$$

Where:

T: temperature.

h: Planck's constant = 6.62606957 × 10^{-34} joule·s ,

k: 1.3806488 × 10-23 joule/K.

m_e and m_h: are the effective masses of electrons and holes respectively; E_{GO}: is the band gap linearly extrapolated to absolute zero.

B: is a constant which is essentially independent of temperature.

By neglecting the dependence of the other parameters (others of n_i) in eq. 4.3 on temperature, and by substituting eq. 3.4 in eq. 3.3:

$$I_o = qA\,\frac{D}{LN_D}BT^3\exp\left(-\frac{E_{Go}}{kT}\right) \approx B'T'\exp\left(-\frac{E_{Go}}{kT}\right) \qquad (3.5)$$

Where B' is a temperature independent constant. A constant, γ, is used instead of the number 3 to incorporate the possible temperature dependencies of the other material parameters.

For silicon solar cells near room temperature, I_0 approximately doubles for every 10 °C increase in temperature. [6]

The impact of I_0 in open circuit voltage can be calculated by substituting the equation of I_0 (eq. 3.5) in the equation of open circuit voltage (Eq. 3.2)

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{I_{sc}}{I_o}\right) = \frac{kT}{q}[\ln I_{sc} - \ln I_o]$$
$$= \frac{kT}{q}\ln I_{sc} - \frac{kT}{q}\ln\left[B'T^{\gamma}\exp\left(-\frac{qV_{Go}}{kT}\right)\right]$$
$$= \frac{kT}{q}\left(\ln I_{sc} - \ln B' - \gamma\ln T + \frac{qV_{Go}}{kT}\right) \qquad (3.6)$$

Assuming that dVoc/dT does not depend on dIsc/dT, dVoc/dT, Where $E_{G0} = qV_{G0}$, so:

$$\frac{dV_{oc}}{dT} = \frac{V_{oc} - V_{Go}}{T} - \gamma\,\frac{k}{q} \qquad (3.7)$$

The above equation shows that the temperature of solar cell depends on open circuit voltage of the cell (typically open circuit voltage at STC).

Solving the equation for silicon gives, with E_{GO} = 1.2 and γ = 3 [6].

$$\frac{dV_{oc}}{dT} = -\frac{V_{GO} - V_{oc} + \gamma \frac{kT}{q}}{T}$$

≈ -2.2 mV per ℃ for S_i Cell (3.8)

From the above, it is found that the reduction in open circuit voltage per C° is 2.2 mV per C° per cell.

The value in equation 3.8 has minus sign, this means the open circuit voltage decreases as temperature increases.

This value will be verified by simulation and experimental results later.

As open circuit voltage decreases with temperature increase, the short circuit current I_{SC} for Si increases slightly, about 0.0006 amp per C°. [6]. the effect of temperature on the maximum power can be estimated by – (0.004 to 0.005) W per C°. [6].

These values are for single silicon solar cell, assuming that we have a PV module with 50 cells, the reduction in open circuit voltage will be about 2.2 * 50 = 110 mV per C° for the module.

3.2.3 Radiation and solar cell temperature

In this section we will discuss how the solar radiation affects the cell temperature and the relation between them. A real measured data (measured at Jericho in Palestine) will be used to find the relation.

3.2.3.1 The relation between the solar radiation and the cell temperature.

Some of the sunlight doesn't reach the earth, it is reflected back to the sky before entering the atmospheric, and the other part reaches the earth to be the source of all our energy.

Solar radiation, is the only energy input on the PV module, and this input will strikes the module. Some of this radiation (sun light) will be absorbed by the module which converted to electrical and heat, the rest of light will be reflected. Table 3.1 shows the combinations of sunlight.

Table 3.1: Sunlight combinations

	Wavelength	Percentage of Sunlight
Ultraviolet	10 nm - 380 nm	46%
Violet	380 - 450 nm	7%
blue	450 - 495 nm	
green	495 - 570 nm	
yellow	570 - 590 nm	
orange	590 - 620 nm	
red	620 - 750 nm	
Infrared	750 - 1,000,000 nm	47%

Solar cells are made from silicon (most used), n-type and p-type semiconductor material that use the visual light spectrum to generate electricity. Solar radiation with wavelengths of 380 nm to 750 nm (violet to red) strikes the material with enough energy to knock electrons from their weak bonds and create an electric current.

The unused wavelengths (ultraviolet & infrared) do not have enough energy to activate the electrons and are absorbed as heat.

3.2.3.2 Heat Generation and Heat Losses in PV modules (solar cells)

Heat Generation

For typical commercial PV module operating at its maximum power point, only 10% to 15% of the incident sunlight is converted to electricity, the remaining percentage is converted to heat. So a PV module exposed to sunlight generates heat as well as electricity.

There are some factors affect the generation of heat (heating the module):

- The absorption of infrared light (low energy) by solar cells.
- The electrical operation of cells (means the current flows through shunt and series resistance).
- The reflection from the top surface.
- Absorption of sunlight by empty regions. There are the regions that not covered by solar cell in the module As indicated in figure 3.2.
- The packing material of solar cells.

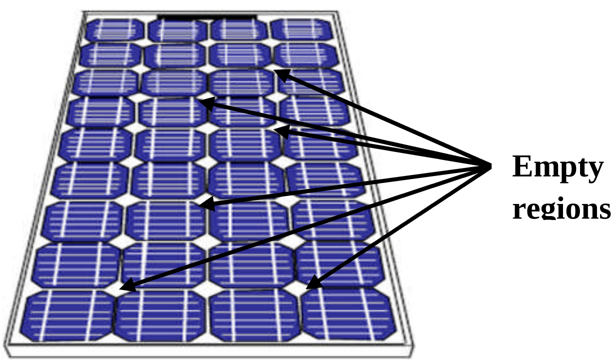


Figure (3.2): Empty regions in PV module.

Heat Losses

Figure 3.3 shows the equilibrium of heat in PV module. This equilibrium between the sunlight (heat generated in the PV module by the sunlight) and heat losses from the PV module. Generally there are three mechanisms in which heat can be lost from the PV module, convection, conduction, and radiation.

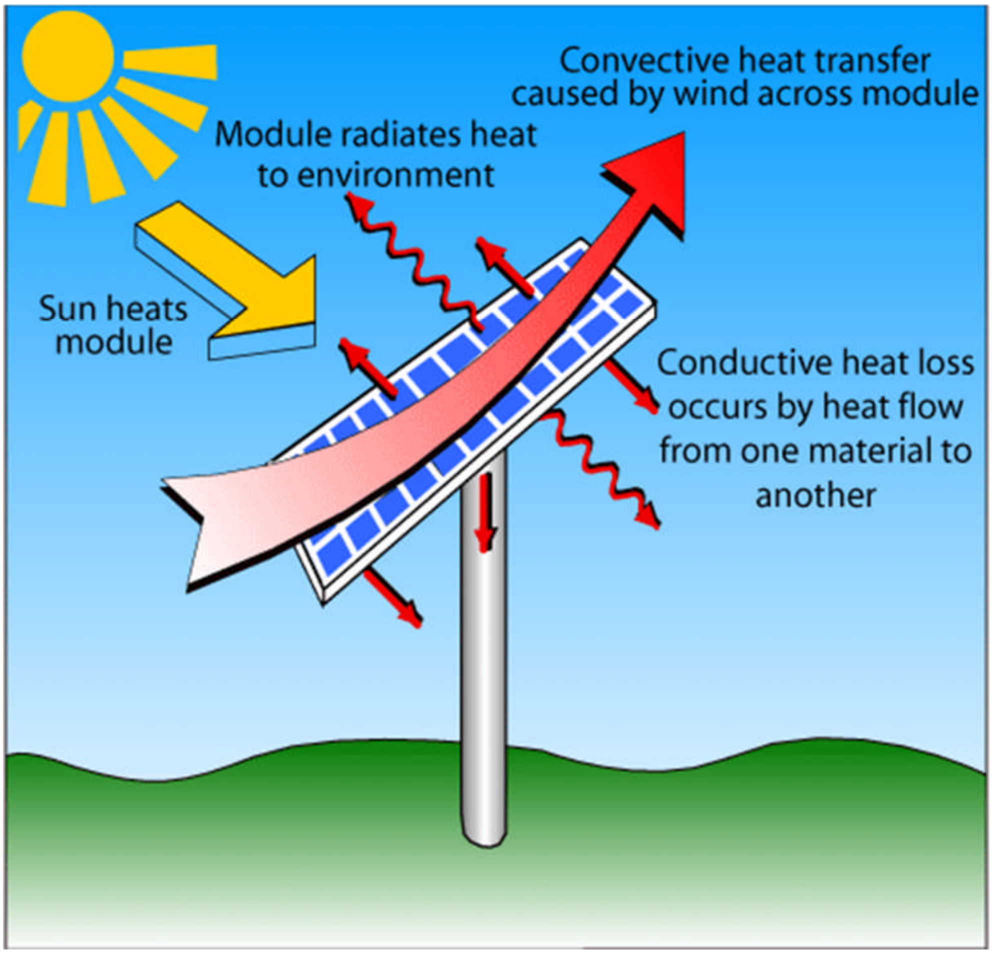


Figure (3.3): PV module heat equilibrium. [63

Conductive losses:

The conductive losses is due to contact between the PV module and other materials – including the surrounding air – this ability to transfer heat depends on the thermal resistance and the configuration of the material used to cover the solar cells, and of the material which is in contact with the module.

$$\mathrm{q} = \frac{K_T}{\mathrm{s}} \times \mathrm{A}\,(\mathrm{T_{sc}} - \mathrm{T_{am}}) \qquad (3.9)$$

Where:

q: heat transfer (W)

A: heat transfer area (m2)

K_T: Thermal Conductivity of material (W/m℃)

S: material thickness (m)

U: k / s : Coefficient of Heat Transfer (W/m^2K)

T_{sc} : solar cell temperature (C°)

T_{am}: ambient temperature (C°).

Convection losses:

Convection heat losses is due to air movement across the surface of the PV module. It is given by the following equation:

$$\mathrm{q} = \mathrm{h_c}\,\mathrm{A}\,(\mathrm{T_{sc}} - \mathrm{T_{am}}) \qquad (3.10)$$

Where:

q: heat transferred per unit time (W)

A: heat transfer area of the surface (m^2)

h_c: convective heat transfer coefficient ($W/m^2°C$).

T_{sc} : solar cell temperature (°C)

T_{am}: ambient temperature (°C).

Radiation Losses:

The last technique of heat losses is the radiation, as PV module (like any object) will emit radiation (heat) depending on its temperature. The heat losses by radiation can be given in the following equation:

$$q = \varepsilon\sigma\,(T_{sc}^4 - T_{am}^4)\,A \qquad (3.11)$$

Where:

q: heat transferred per unit time (W)

A: area of the surface (m^2)

σ: 5.6703 10^{-8} (W/m^2K^4) - ***The Stefan-Boltzmann Constant***

ε = emissivity coefficient of the object

T_{sc} : solar cell temperature (C°)

T_{am}: ambient temperature (C°).

In PV module case, most losses occurred by convection and radiation so by ignoring the conducting losses, the equilibrium state can be written as following:

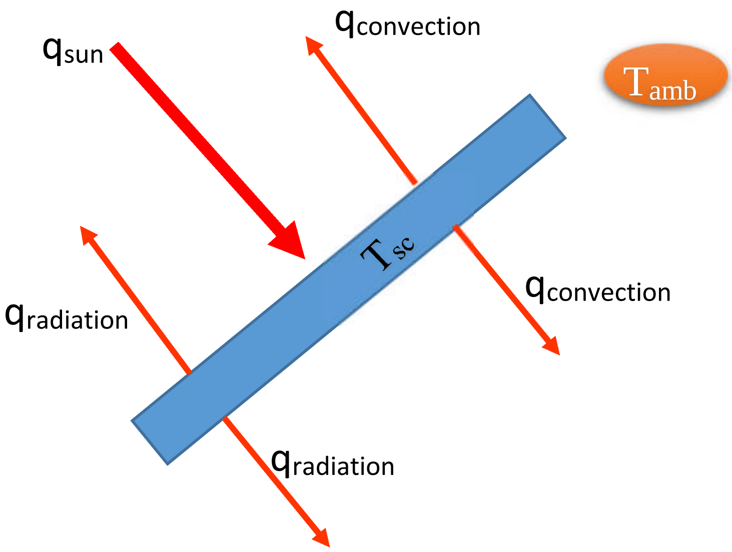


Figure (3.4): Energy balance for a PV module.

$$E_{in} = E_{out}$$

$$\alpha\, G = \varepsilon_{glass}\, \sigma \left(T_{sc}^4 - T_{amb}^4 \right) + \varepsilon_{back}\, \sigma \left(T_{sc}^4 - T_{amb}^4 \right) + 2(h_c\, (T_{sc} - T_{amb})) + \text{Electrical energy} \tag{3.12}$$

Where:

α: Module absorptivity.

G: Global irradiance on module.

ε_{glass}: Glass emissivity.

ε_{back}: Back of module emissivity.

σ: Stefan-Boltzmann constant.

h_{c}: convective heat transfer coefficient.

Practically, these losses can be considered as wanted losses. So the main idea of cooling solutions is to maximize these heat losses as much as possible to decrease the operating cell temperature.

3.2.3.3 Radiation Vs Cell Temperature

Cell temperature mostly depends on the solar radiation intensity and on the ambient temperature. This relation will be discussed using real measured data in Palestine for solar radiation, ambient temperature, and module temperature.

Equation 3.13 describes the relation between solar radiation and ambient temperature and cell temperature.

$$T_c = T_{amb} + \frac{NOCT-20}{800}\, G(t) \qquad (3.13)$$

Equation 3.14 can be used to determine approximately the cell temperature.

$$T_c = 0.0256\, G(t) + T_{amb} \qquad (3.14)$$

Three measured data groups from an installed PV system in Jeftlek area will be used, sample during summer and autumn, sample during winter and a sample during spring, as illustrated in the following tables:

Table 3.2 shows the data measured of the PV system at Jeftlek area. (During the sunny day in June).

Table 3.2: measured data in June.

Time	Solar radiation (G) (W/m^2)	Ambient temperature (T_{amb}) ℃	Module temperature (T_{mod}) ℃
5	0	24.5	23
6	0	24	23
7	50	25	26
8	190	27	32
8:30	300	31	36
9	390	32	42
9:30	500	32	49
10	620	36	50
10:30	700	35.5	52
11	800	36	55
11:30	900	37	59
12	950	36.5	57
12:30	980	37	57
13	1000	38	58
13:30	1050	39	62
14	1000	40	63
14:30	950	43.5	68
15	910	40	53
15:30	850	39	52
16	800	38.5	50
17	600	37	46
18	380	33	43
19	110	32	36
20	0	29	32

Figure 3.5, shows the curves generated from table 3.2.

First curve shows the irradiance behavior during the day, where we can say that it was a clear sky day during all measurements procedure as the curve change almost sinusoidal with respect to day hours.

The second curve shows the variation of ambient temperature.

The last curve shows the module temperature, which is the most important curve, as our focus here is on module (solar cell) temperature effect on the output power from the module. From this curve we can see that the module temperature can reach about 70℃ , which is so high for the module, with respect to average NOCT for PV modules. This high temperature cause a significant decrease in output voltage and power of the module.

From this figure, we can see how the temperature of the module changes as ambient temperature and solar radiation changes. Also, it is clear that the module temperature is almost less than (or equal) the ambient temperature during night when there is no sun.

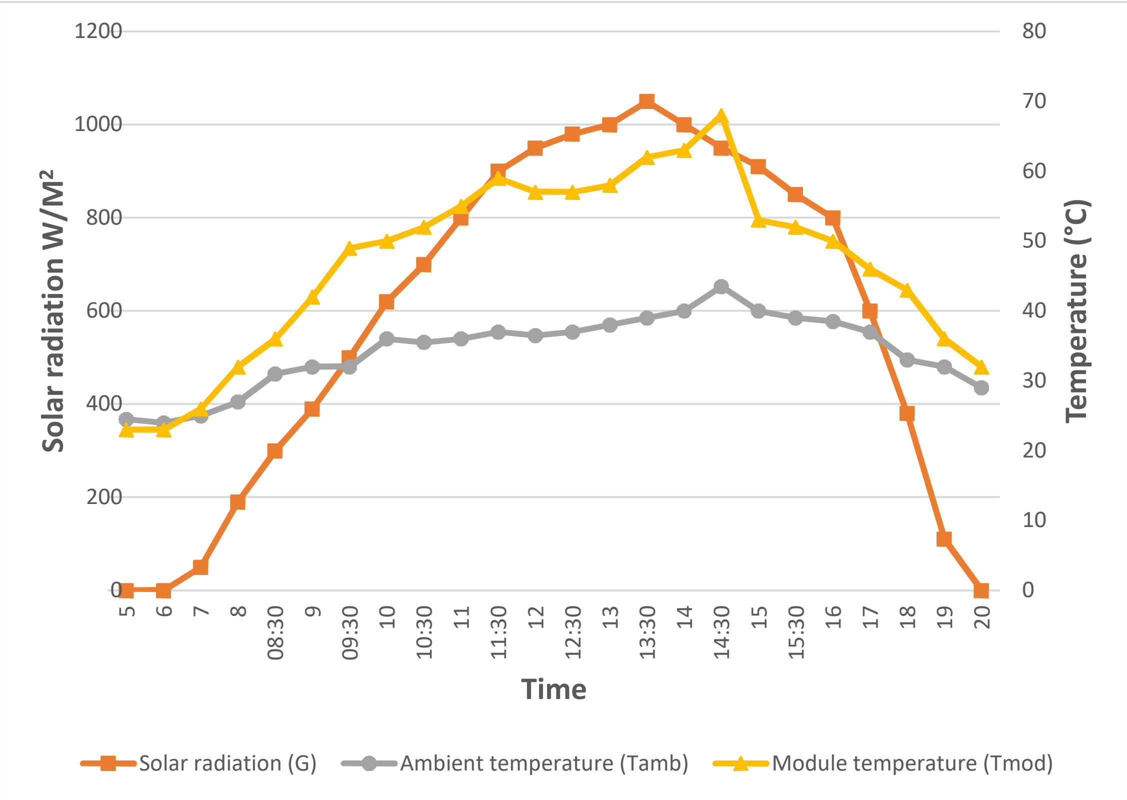


Figure (3.5): The variation of PV module temperature during the day hours in a clear sunny day in June with respect to solar radiation and ambient temperature.

Table 3.3 shows the data measured of the PV system at Jeftlek area.

(During the sunny day in December).

Table 3.3: measured data in December.

Time	Solar radiation(G) (W/m^2)	Ambient temperature (T_{amb}) ℃	Module temperature (T_{mod}) ℃
5	0	9.5	5
6	0	9.5	5
7	20	9	5
8	140	11	11
8:30	200	14	15
9	340	14.5	20
9:30	400	16.5	26
10	500	18.5	30
10:30	570	19	34
11	650	18	34
11:30	690	21	36
12	700	20.5	36
12:30	690	20.5	38
13	650	21	33
13:30	600	21	32
14	520	21.5	32
14:30	420	22	30
15	300	21	30
15:30	170	20.5	25
16	30	18.5	20
17	0	14	12
18	0	13.5	11
19	0	12.5	11
20	0	12	10

Figure 3.6, shows that the maximum module temperature is about 38 ℃ which is very close, and less than the average NOCT.

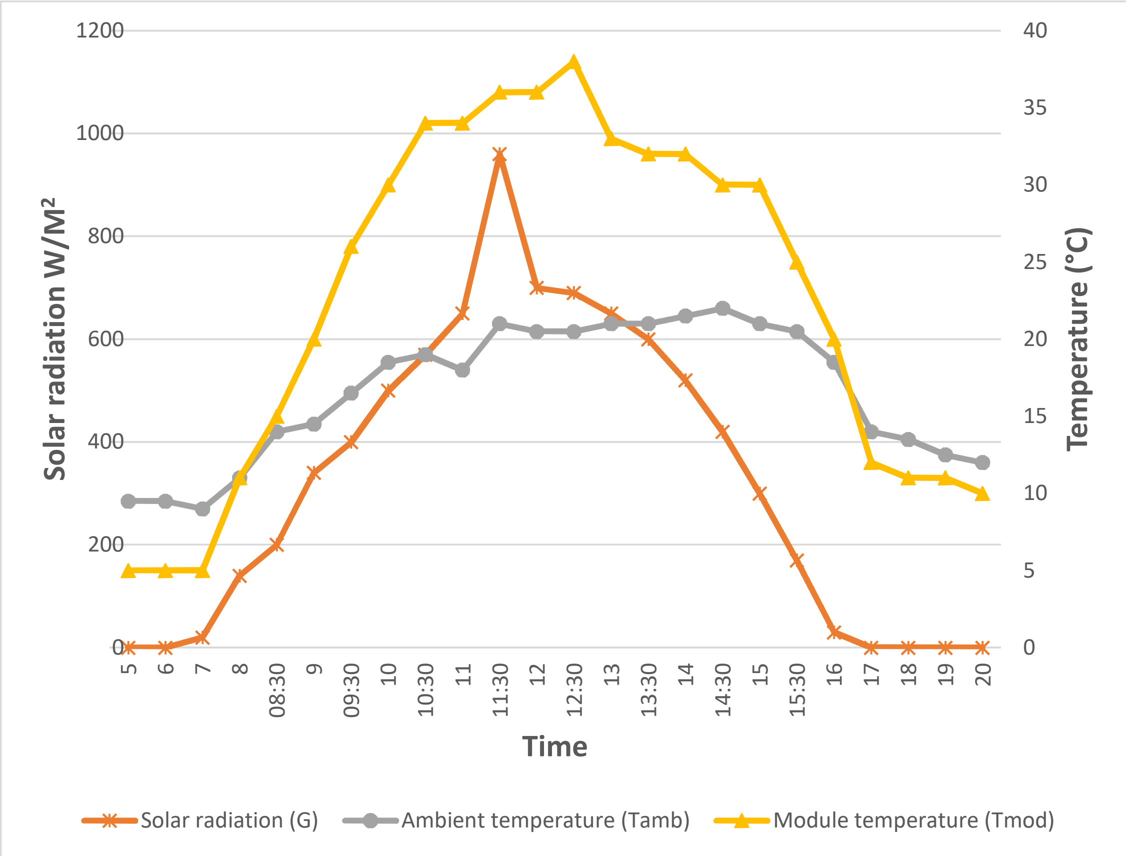


Figure (3.6): The variation of PV module temperature during the day hours in a clear sunny day in December with respect to solar radiation and ambient temperature.

Table 3.4 and figure 3.7 shows the data measured of the PV system at Jeftlek area. (During the sunny day in March) [1]

Table 3.4: measured data in March.

Time	Solar radiation (G) (W/m^2)	Ambient temperature (T_{amb}) ℃	Module temperature (T_{mod}) ℃
5	0	16	14
6	0	15	13
7	100	15	14.5
8	280	19	20
8:30	400	20	25
9	550	24	29
9:30	650	24	34
10	700	28	41
10:30	800	27.5	43
11	850	28	45
11:30	880	29	50
12	900	30.5	51
12:30	870	32.5	54
13	700	29	45
13:30	800	30.5	52
14	750	31	52
14:30	650	30	49
15	550	30	45
15:30	400	30	42
16	220	29	39
17	30	25.5	27
18	0	21	20
19	0	20	15.5
20	0	19	15

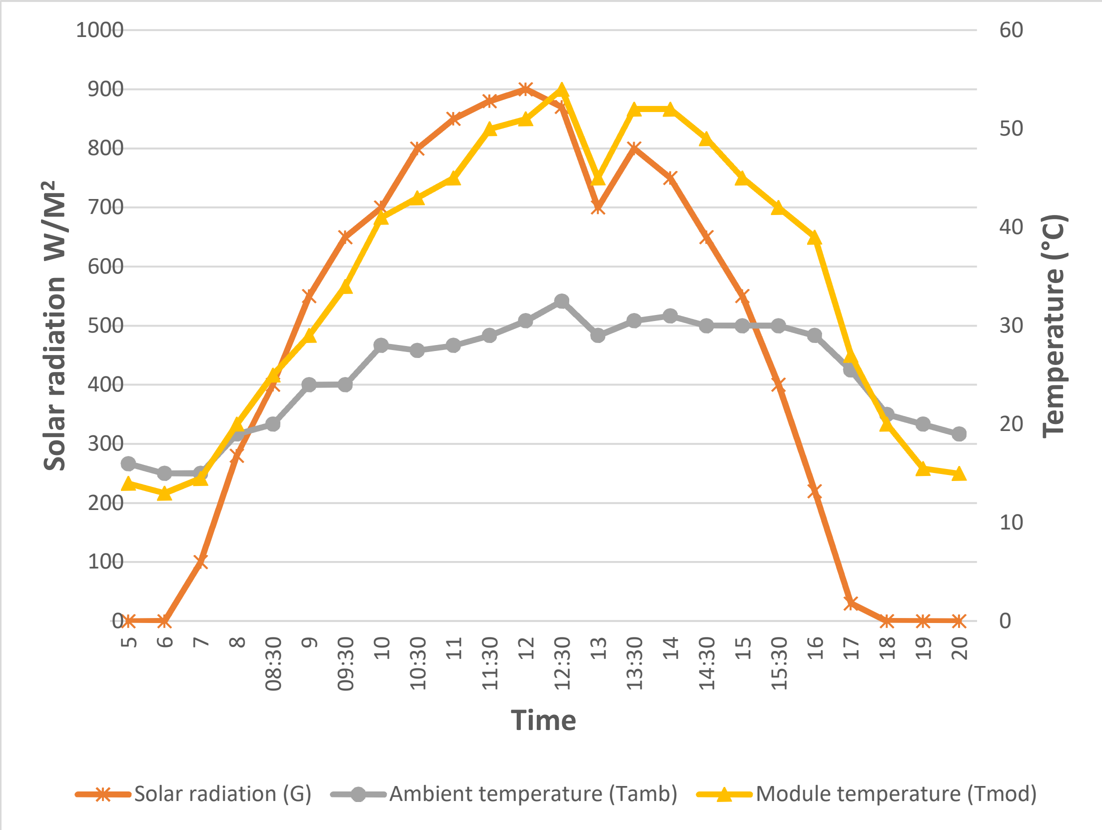


Figure (3.7): The variation of PV module temperature during the day hours in a clear sunny day in March with respect to solar radiation and ambient temperature.

From the measured data, the module temperature in March can reach about 55 ℃ where the irradiance can reach 900 W/m^2.

Generally the maximum module temperature could be reached during the summer and autumn as they have maximum irradiance, also during spring the module temperature is significantly high and it will have a remarkable effect on the module output. But in winter the module temperature stays close to the average NOCT which is not bad. So from all above we can conclude that the need for cooling the PV modules is high during summer, autumn and spring, and low during winter.

Taking the data measured in summer, and using the equation 3.14, we can calculate the module temperature theoretically ($T_{mod.theory}$), table 3.5 shows the results of this calculation.

Table 3.5: Measured and Calculated data in June.

Time	Solar radiation (G) (W/m^2)	Module temperature (T_{mod}) ℃ Measured	Ambient temperature (T_{amb}) ℃	Module temperature ($T_{mod.theory}$) ℃ Theoretically
5	0	23	24.5	24.5
6	0	23	24	24
7	50	26	25	26.28
8	190	32	27	31.864
8:30	300	36	31	38.68
9	390	42	32	41.984
9:30	500	49	32	44.8
10	620	50	36	51.872
10:3	700	52	35.5	53.42
11	800	55	36	56.48
11:3	900	59	37	60.04
12	950	57	36.5	60.82
12:3	980	57	37	62.088
13	1000	58	38	63.6
13:3	1050	62	39	65.88
14	1000	63	40	65.6
14:3	950	68	43.5	67.82
15	910	53	40	63.296
15:3	850	52	39	60.76
16	800	50	38.5	58.98
17	600	46	37	52.36
18	380	43	33	42.728
19	110	36	32	34.816
20	0	32	29	29

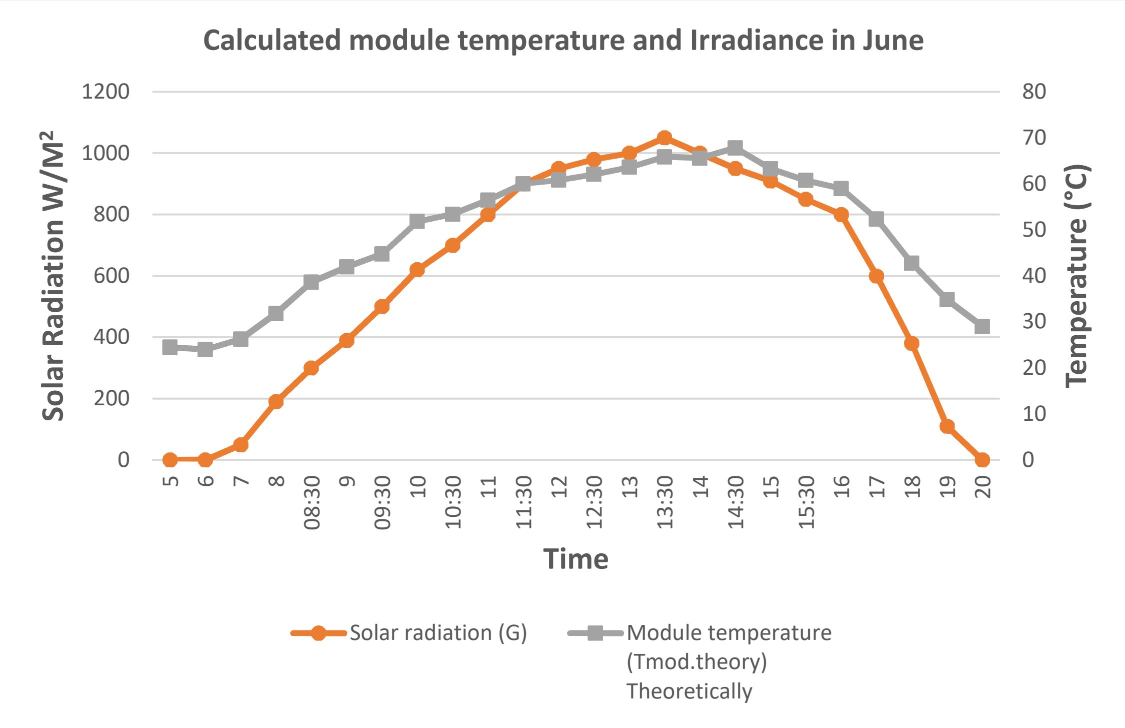


Figure 3.8 shows the irradiance (radiation intensity) and the module temperature. From this, it is clear that the temperature of the module is highly depending on the irradiance. As the irradiance increases, the sunlight falling on the surface of the module also increases, so the energy input to the PV module increases. This makes the module temperature increases. Figure 3.15 shows that the maximum module temperature reached occurred between o'clock 13:30 and 15, and the maximum measured irradiance was at o'clock 13:30.

Generally, there is a positive relation between the irradiance (solar radiation intensity) and the temperature of the PV module.

Now if this relation is established again, but between the irradiance and the measured module temperature, we can see that this fact (the equation 3.14) is true and approved. Figure 3.9 shows the relation between the irradiance and the measured module temperature (real measured data).

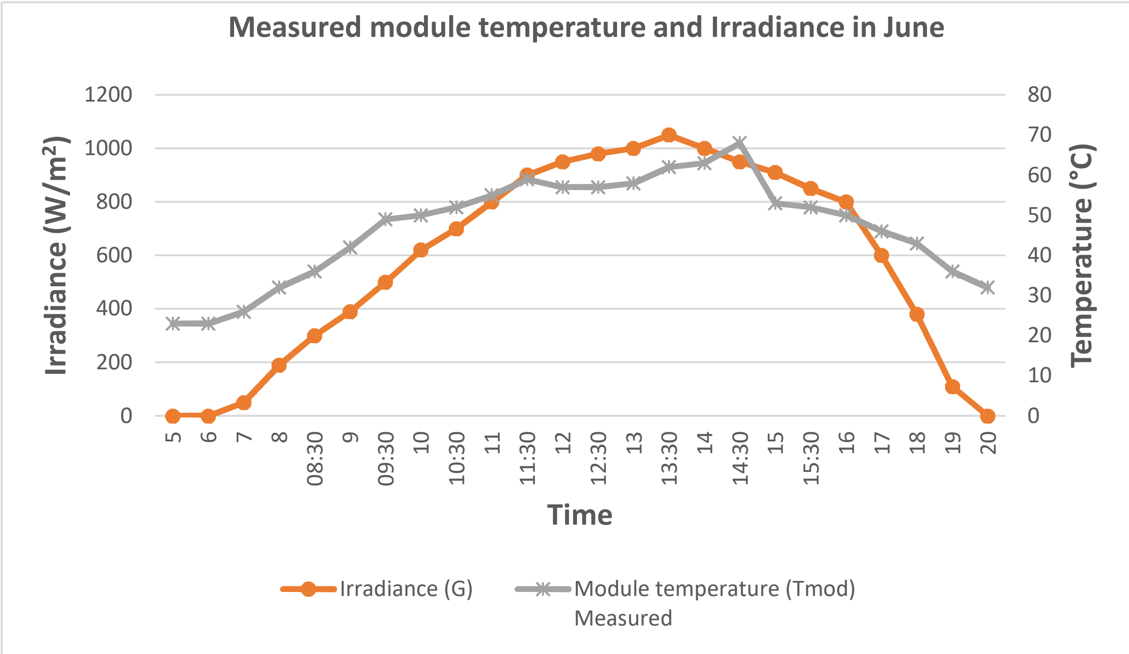


Figure (3.9): Measured module temperature and solar radiation in June.

Figure 3.10 shows that there is a bit difference between the measured and the calculated module temperature, (higher or lower) especially afternoon (after o'clock 17). This small difference is because of other parameters such as wind speed, sunset, cloudy, and the difference in the ambient temperature. But generally the equation 3.14 can expect the cell (module) temperature accurately with small error which can be neglected, especially during the hours of clear sunny day.

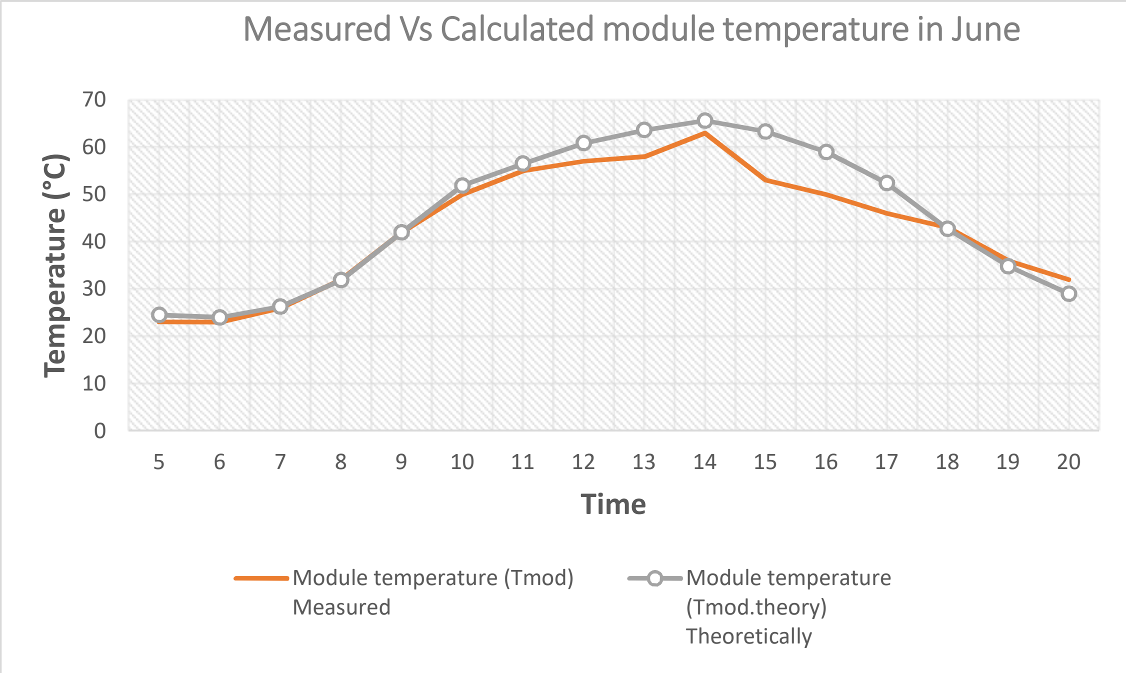


Figure (3.10): Measured Vs Calculated module temperature in June.

3.2.4 Module Temperature and Output Power

Before starting modeling the output of the PV, we need to know what is the voltage temperature coefficient and the current temperature coefficient and their effects on the voltage and current of the solar cells. In section 3.2.1.2 we mentioned that in general and as an average values, the voltage temperature coefficient is about -3.7 * 10^{-3} mV/ °C, and the current temperature coefficient is about 6.4 * 10^{-4} mA/°C. (These values are for crystalline Silicon cells). But actually the calculation of these coefficients depends on many parameters and characteristics of each solar cell, so they may differ from cell to other depending on the material, the manufacturing technology, the bandgap characteristics and others. One has no need to calculate or measure these coefficients because these values and others are provided in the data sheet of any PV module from the manufacturer of that module.

These coefficients are important and useful in calculating the changes in voltage and current of the PV module as temperature increases. In other words they are used to calculate the PV module output at each value of the module temperature (cell temperature).

As mentioned before, the degradation in open circuit voltage for silicon cell is about of -2.2 mV per ℃-cell.

Using theses coefficients and using a correlation equation for the voltage, current and power of the PV module, the output of the module can be calculated (accurately) at any cell temperature. To know how much power will be generated from the module in any situation (temperature).

Some manufacturers provide these temperature coefficients (voltage, current and power) as a percentage of the open circuit voltage, short circuit current and power at STC (standard test conditions) values. So in average the open circuit voltage temperature coefficient could be about -0.32 %/°C, which means the voltage will decrease by about 2 mV for increasing of module temperature by 1 °C.

3.2.4.1 PV module output without the effect of cell temperature.

Considering the STC value of T_c, then considering $T_c = T_{amb}$.

First, in this part the I-V curve will be generated (by simulation) at different cell temperatures (at T_c = 25, 35, 45, 55, 65℃). The equations from 3.15 to

3.17 will be used to generate the I-V curve using MATLAB program. The curves are as bellow:

$$i = I_{ph} - I_0 \left(e^{\frac{v+iR_s}{n_s v_t}} - 1 \right) - \frac{v+iR_s}{R_{sh}} \quad (3.15)$$

$$R_{s-max} = \frac{V_{oc} - V_{MPP}}{I_{MPP}} \quad (3.16)$$

$$v_t = \frac{1.25kT}{q} \quad (3.17)$$

Where:

I_{ph}: Current generated by the incident light [A]

I_0: Diode saturation current [A]

R_{sh}: Cell parallel (shunt) resistance [ohm]

R_s: Cell series resistance [ohm]

n_s: Number of PV Cells connected in series

v_t: Diode thermal voltage(=akT/q)[V]

a: Diode quality(ideality) factor

k: Boltzmann's constant (1.381×10^{-23}) [J/K]

q: Charge of the electron (1.602×10^{-19}) [C]

T: Kelvin Temperature at standard test condition [K]

Secondly, the output of the module at STC will be discussed and simulated along the year, taking into consideration that the value of the cell temperature at STC is 25℃ .

Then the output of the module will be discussed and simulated along the year considering that the temperature of the module is always equal to the ambient temperature (ignoring the effect of module construction and the solar radiation).

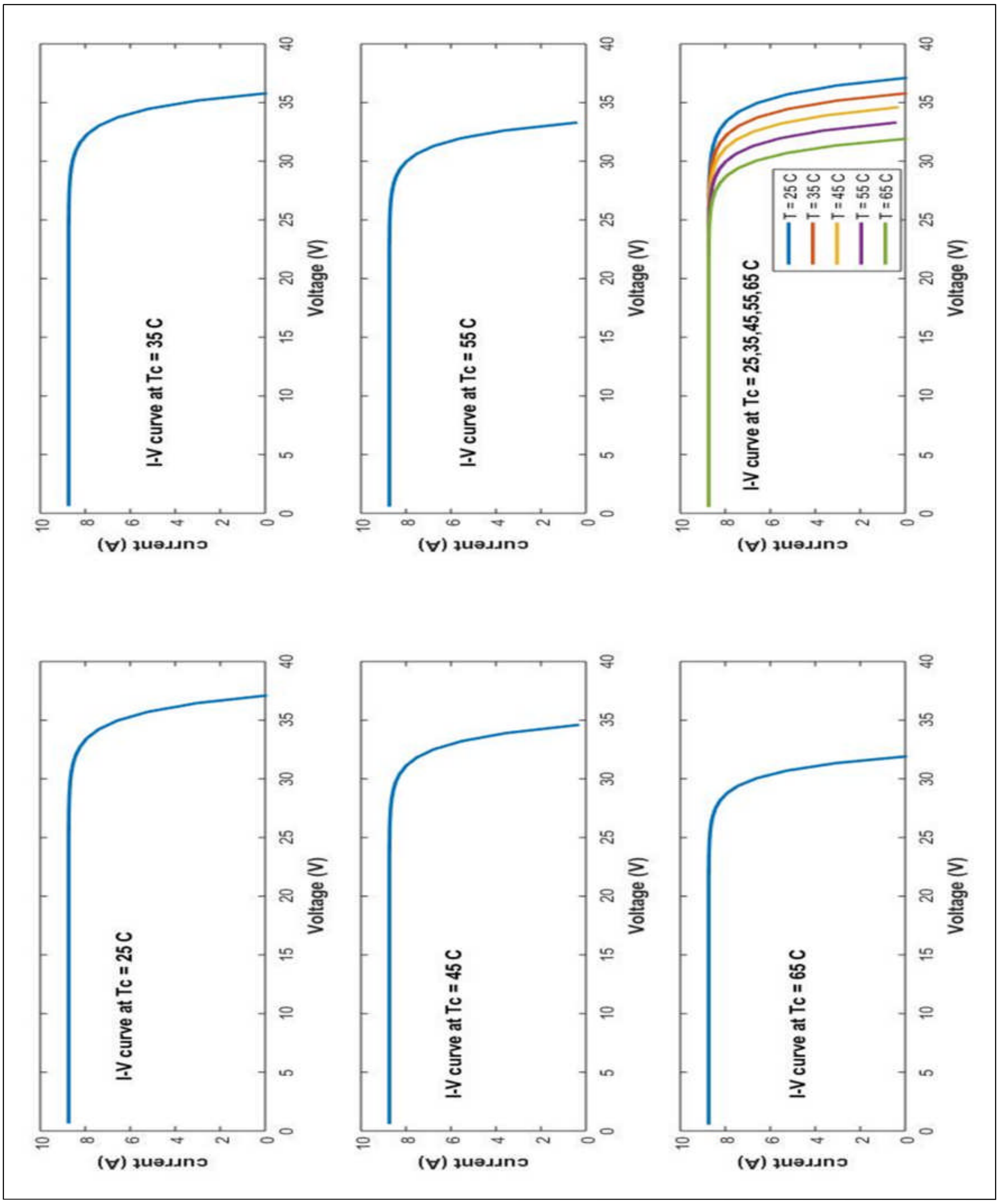


Figure (3.11): I-V curve of a 250 W Hanwha module, at cell temperature equal to 25, 35,45,55,65°C.

The simulation will be based on a 250W PV module, manufactured by Hanwha Company. The specification and characteristics of this module are shown in the module datasheet in Appendix A.

The following equations will be used to estimate the cell temperature, open circuit voltage and the short circuit current:

1. Cell temperature: [1]

$$T_c = T_{amb} + \frac{NOCT - 20}{800}\, G(t) \qquad (3.13)$$

2. Open circuit voltage: [1]

$$V_{oct} = V_{oc_{stc}}(1 + h_v(T_c - 25)) \qquad (3.18)$$

3. Short circuit current: [1]

$$I_{sct} = I_{sc_{stc}}(1 + h_i(T_c - 25)) \qquad (3.19)$$

In order to show the effect of cell temperature on the output of a PV module, the output of this PV module at different temperatures should be found (measured or calculated) during a certain period. In our case we will discuss the output of this module during a year.

Output at T_c = 25 ℃ :

The curves below (figure 3.12) show the calculated parameters (V_{oc} , I_{sc}, output power) of the module at a constant cell temperature of 25 ℃ during all the year. (Excepting the no-sun hours)

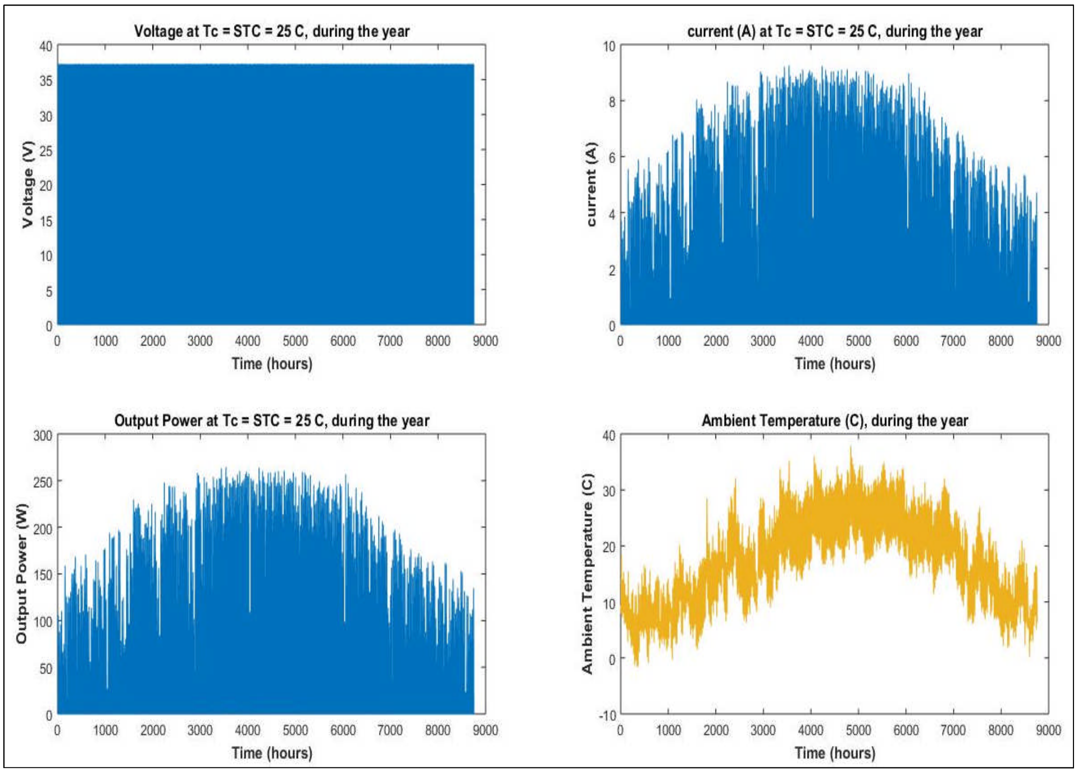


Figure (3.12): PV module Output at constant Tc = 25°C.

From figure 3.12 we can notice that the output power of the module can reach its peak output, 250 W, during the peak sun radiation. The maximum value of the output power during the year was found to be about 254 W, which is bit more than the peak power.

The figure also shows the open circuit voltage. It seems to be fixed, but, actually it is not. This is due to the long interval used to plot the curve. Figure 3.13 shows the open circuit voltage between the hours 5000 and 5500:

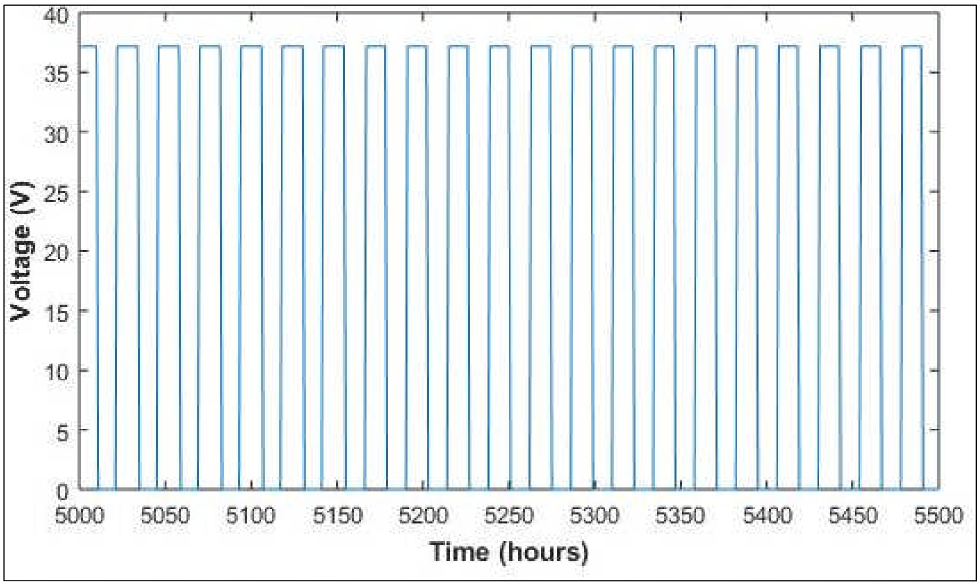


Figure (3.13): Open circuit voltage between hours 5000 and 5500.

From the figure, it can be observed that the voltage is zero at night hours. Other point about the value of open circuit voltage is it doesn't jump to highest value instantly at the sun rise, but it increases logarithmically with radiation (from 0 to about 165 W/m^2) [1]. Where it reaches its maximum value and remain constant. Figure 3.13 shows the value of open circuit voltage for 30 hours, Calculated by simulation – MATLAB.

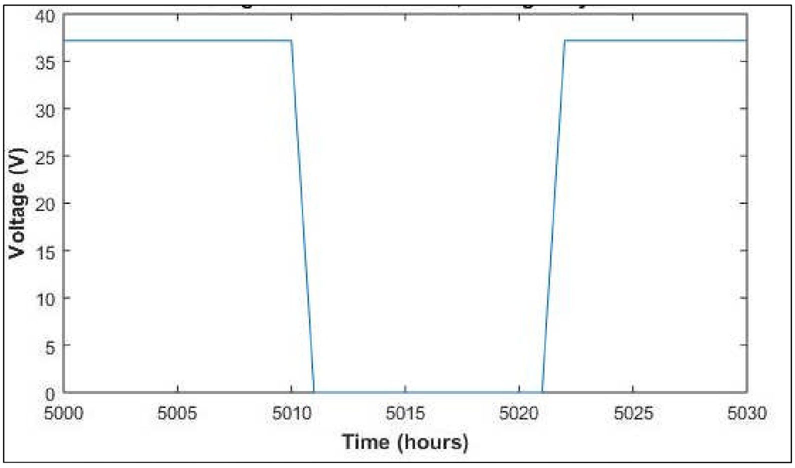


Figure (3.13): Open circuit voltage of PV module during 30 hours.

Using simulation, the output energy of the PV module can be calculated during the year. As discussed hereafter:

The summation of the output energy during the 8760 hours of simulation is equal to 478 kWh.

This energy amount is very close to the expected amount from this module using the peak-sun-hours (PSH) equation. Which is as follows:

Energy per day = peak power of module (Plant) * PSH (3.17)

As the amount, in average, of the peak sun hours in Palestine equal to 5.4 hours [1], the energy expected from the module per day will be 1.35 kWh/day, which corresponds to about 492.7 kWh/year.

Peak sun hours means the yearly average of sunshine hours per day. Where the solar radiation is constant at the value: 1000 W/m^2.

The energy generated from this module at STC cell temperature can be considered as the highest possible energy that can be generated from the module, in other words a perfect situation which is of course unachievable.

Output at $T_c = T_{amb}$:

The curves below (figure 3.14) show the calculated parameters (V_{oc}, I_{sc}, output power) of the module, considering the cell temperature is always equal to the ambient temperature at the measuring time.

Regarding the open circuit voltage, again, it is not constant, it has a constant maximum (saturation) value depending on the operating conditions of the cell (module), but generally it doesn't change with solar radiation after saturation.

The short circuit current changes linearly with solar radiation. Figure 3.15 shows the short circuit current changing through 24 hours of the simulation (through hours 4005 and 4029 of the year).

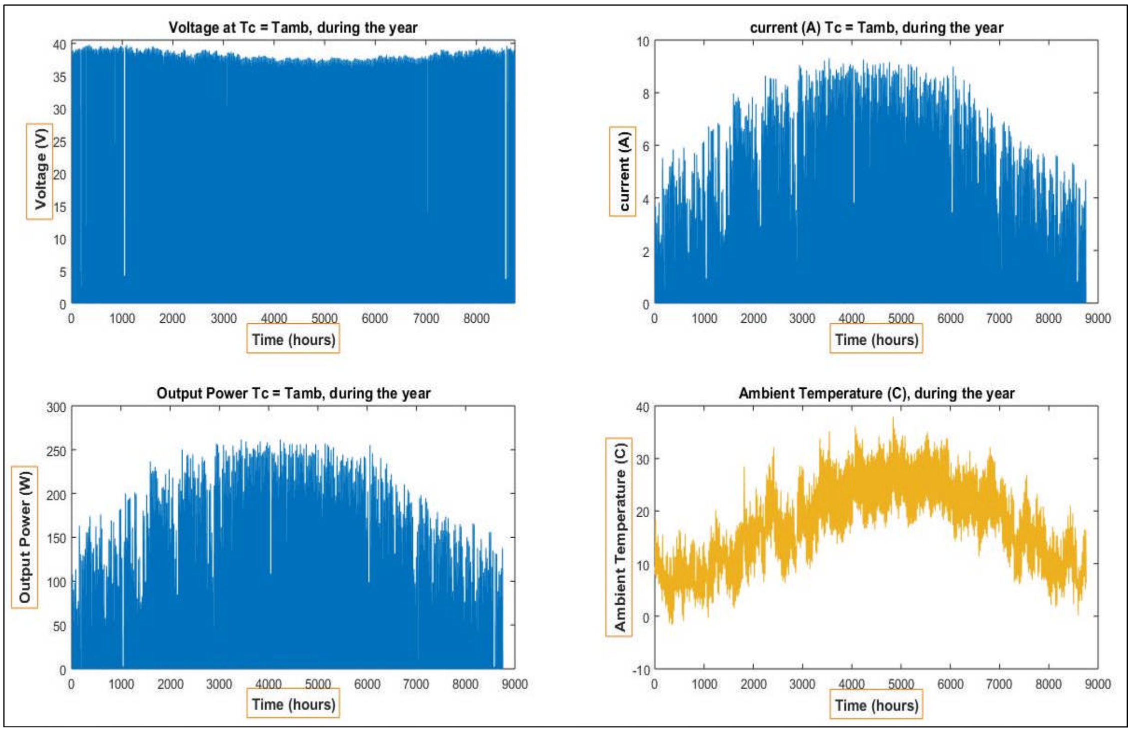


Figure (3.14): PV Module Output considering Tc = Tamb.

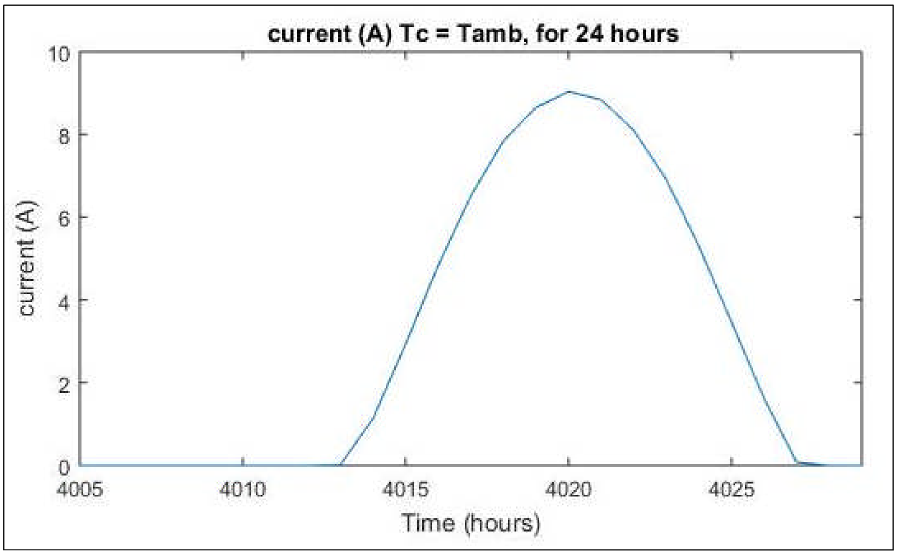


Figure (3.15): PV module short current for 24 hours.

From figure 3.14 and using MATLAB, the maximum value of the output power during the year is about 238 W.

From figure 3.15, we can notice that the short circuit current starts increasing at sunrise until it reaches its maximum at the highest solar radiation, then decreases to zero after sunset.

The summation of the output energy during the 8760 hours of simulation (one year) (the night hours are excepted) is equal to 445 kWh. Since this value represent the summation of the output at each hour, which means that the energy generated by this module during the year is about 445 kWh/year. This value is less than the energy expected from this module when using the PSH equation (equation 3.17) which is equal to 492.7 kWh/year.

The maximum cell temperature (ambient) is 38℃ , and the voltage at this cell temperature is equal to 35.7 V, which is less than the voltage at 25℃ (37.2 V) by 1.5 V. This decrement is due to the increase in cell temperature from 25 to 38℃ .

From this part of simulation (at T_c = 25 ℃ and $T_c = T_{amb}$) it is founded that the output from the PV module is close to the expected output (by PSH equation, and considering the peak power), anyway, this scenario or situation may be the perfect situation as the PV module generates the highest possible energy at the best conditions (regarding to cell temperature). But this situation or conditions can't be achieved in the field without applying modifications or some cooling techniques to keep the cell temperature at the required point.

3.2.4.2 Output Power at NOCT

In this part the simulation will calculate the output power of the PV module at the nominal operating cell temperature NOCT which is equal to 46.5℃ according to the manufacturer data sheet.

Figure 3.16 shows the simulation output:

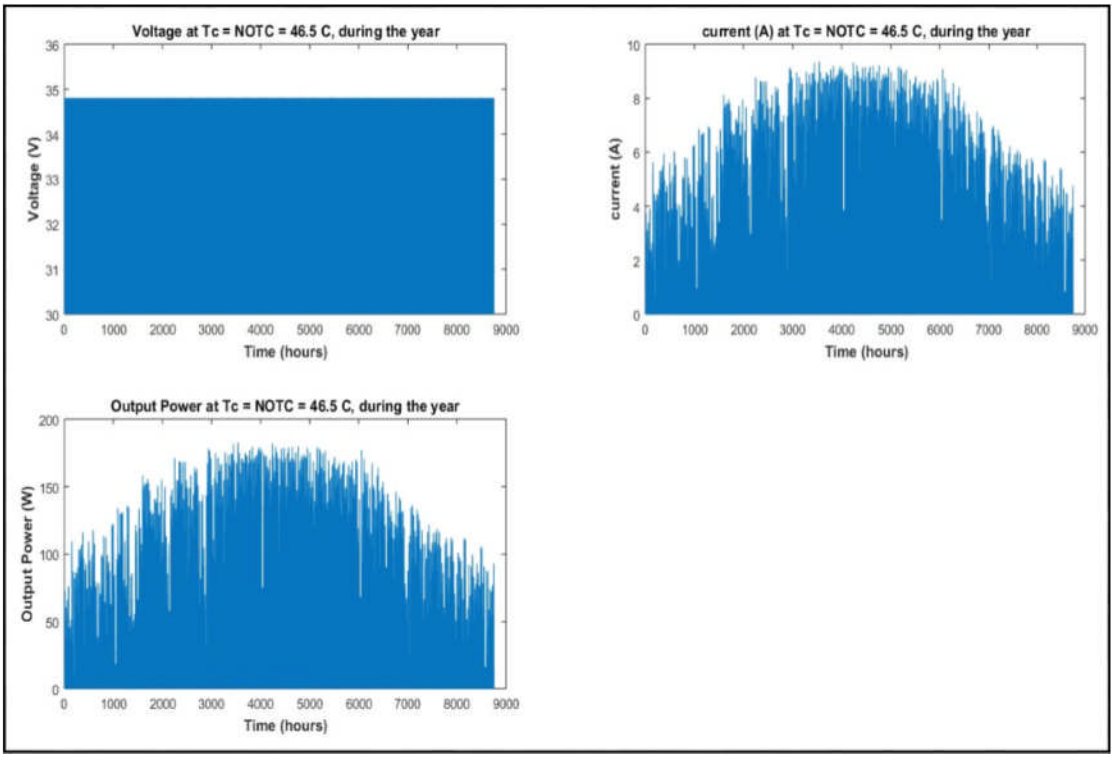


Figure (3.16): PV module Output considering Tc = NOCT.

The open circuit voltage is constant (during the day) and equal to 34.8 V, it is constant because the simulation considers the cell temperature constant during the year which equals to 46.5℃. (Of course the voltage during night is zero).

The maximum output of the module is equal 182.6 W, which is less than the peak power of the module (250 W).

The summation of the output energy during the 8760 hours of simulation (one year) is about 344.2 kWh. So the energy generated from this module during the year could be about 344 kWh/year, which is much less than the energy generated at STC or by PSH calculation.

Comparing the results of the two simulations (T_c = 25 (or T_{amb}) and T_c =NOCT) the difference is about 134 (or 100) kWh per year, which means operating the module at its NOCT will cause more than 100 kWh losses per year.

3.2.4.3 Output at operating cell temperature (T_c)

In this part the simulation will consider the real estimated cell temperature in the calculations (T_c) which is calculated using equation 3.13. Figure 3.17 shows the simulation result.

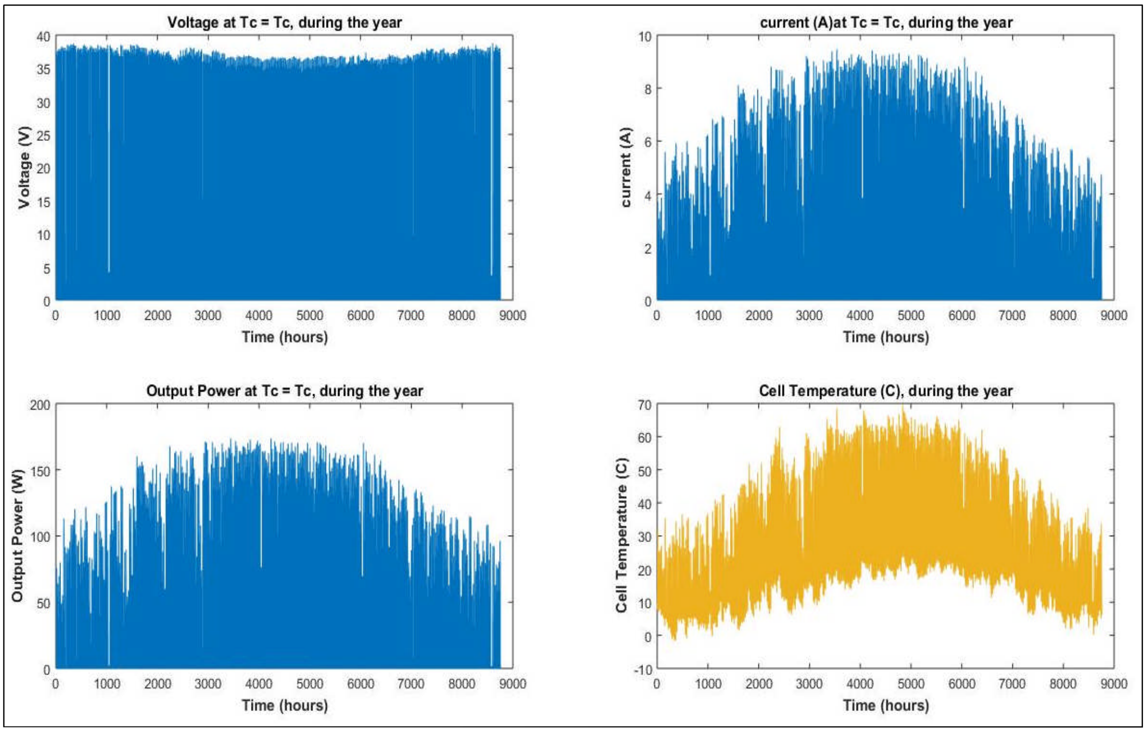
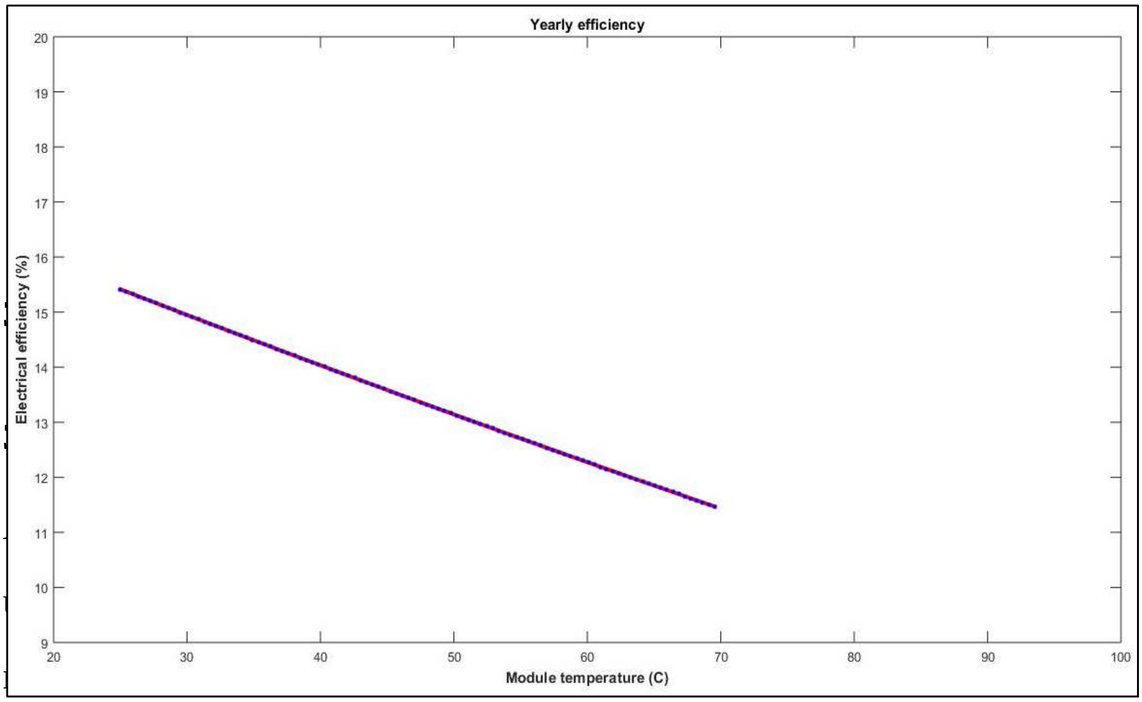


Figure (3.17): PV module output considering Tc.

From the curves above and the simulation results, the maximum cell temperature could reach 69℃, and the open circuit voltage at this cell temperature is 32.2 V, this represents about 5 volt decrease in the voltage.
The maximum power is about 173.6 W, which is less than the peak power and less than the maximum power at NOCT.
The summation of the output energy during the 8760 hours of simulation (one year) is about 331.4 Kwh. So the energy generated from this module during the year could be about 331 kWh/year, which is considerably less than the energy generated at STC or by PSH calculation, also less than the energy generated at NOCT.

3.2.5 Module temperature and efficiency

Figure 3.18 shows the relation between module efficiency and module temperature, this figure is generated by performing the simulation of the module for the whole year several times at several module temperature. (For each iteration, different module temperature was considered)
From the figure, the maximum efficiency can be reached is about 15.5% at module temperature 25℃, and the minimum effieciency reached is about 11.4% at module temperature about 70℃. So it is clear that the temperature rising may decrease the efficiency of the module by about 4%.



difference.

The most common type of thin-films cells is the cells made from a-Si (amorphous silicon). Figure 3.19 shows the relation between open circuit voltage and the cell temperature for an amorphous cell.

Figures (3.20) and (3.21) show the changes in short circuit current and efficiency by temperature changes.

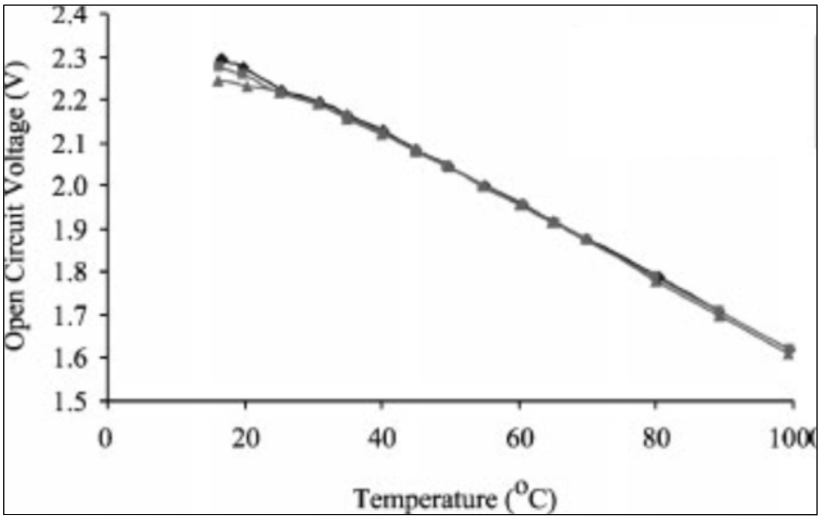


Figure (3.19): Open circuit voltage against cell temperature for a-Si triple-junction [8].

From the figure above, the open circuit voltage decreases with increasing temperature as the behavior of silicon photovoltaic cells.

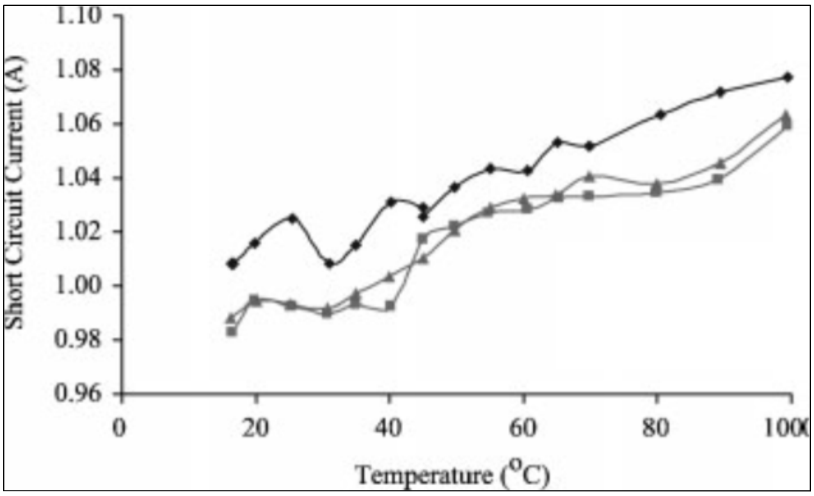


Figure (3.20): Short-circuit current against temperature for a-Si triple-junction [8].

The figure above shows that there is a little increase in short circuit current with increasing temperature, as a result of voltage decrease.

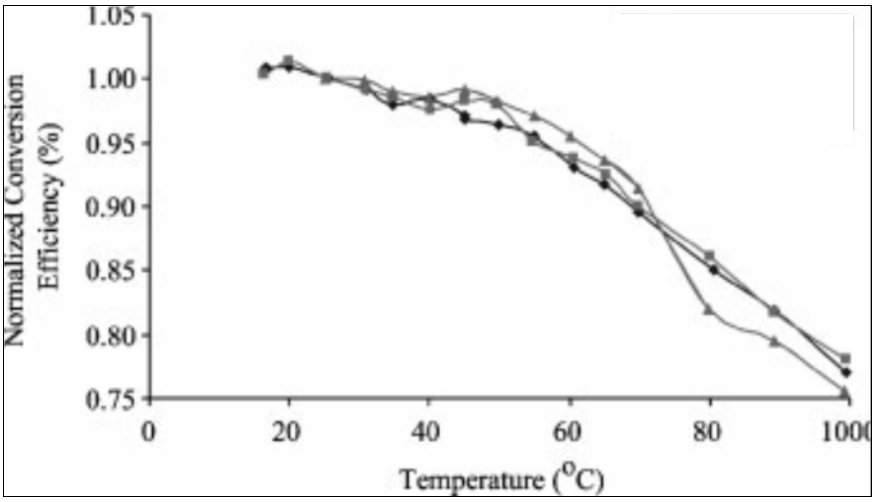


Figure (3.21): Conversion efficiency against temperature for a-Si triple-junction [8].

In general, the efficiency of thin-film cells decreases with temperature increase. This relation is similar to the case of polycrystalline and monocrystalline silicon cells.

3.3.2 Concentrators

The word refers to concentrated solar cells, in other words applying more than one sun (2 suns or more) on the module by concentrating the sunlight on the module by special concentrators (usually parabolic shape), or by focusing large area of sun light on solar cell or module by special optical device.

The using of concentrator technology is growing rapidly. This technique may increase the efficiency of the solar cell up to about 40% by focusing solar radiation. Moreover it has other advantages as:

- Require less installing area and photovoltaic material to capture the same solar radiation and generate same energy.
- High efficiencies (up to 40%) for direct solar radiation.
- Low energy payback time.

On the other side there are some disadvantages or weaknesses for using the solar concentrator:

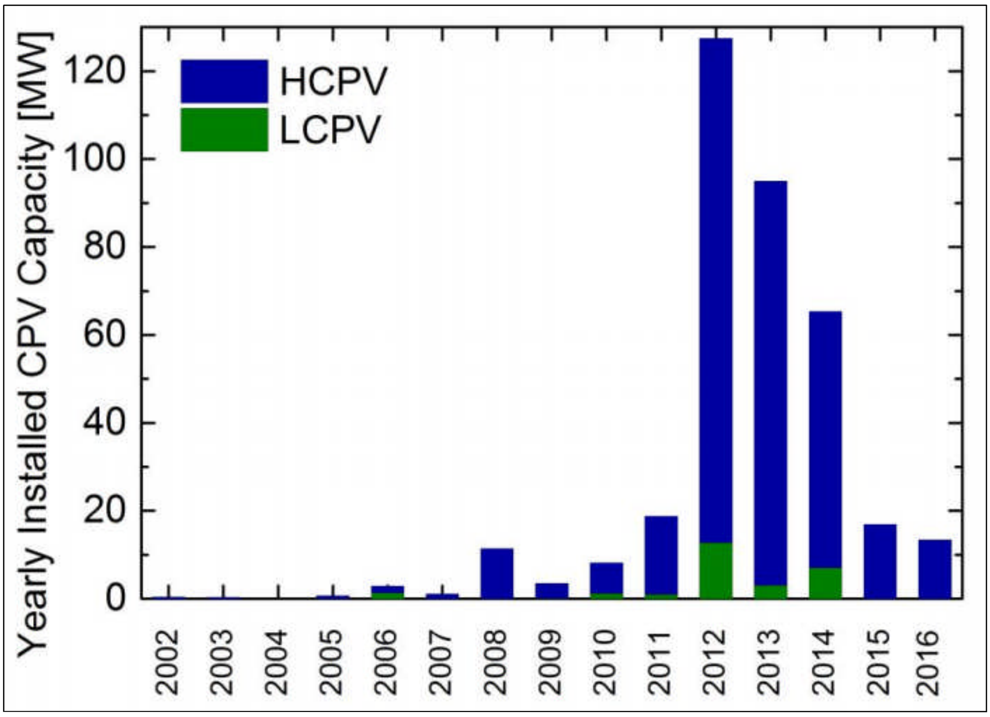
- The cell temperature rise to very high temperature, so it needs continues cooling.
- It doesn't work with diffused radiation, and needs always very accurate tracking system.
- It can't be easily installed in small areas such as rooftops as it needs wide areas.

There are two methods or techniques of concentrating depending on concentration ratio. The Low concentration photovoltaic (LCPV) and High concentration photovoltaic (HCPV). Both require cooling to prevent the failure of the solar cell due to high temperature. Table 4.6 shows the typical concentration ratios for each type.

Table 3.6: Concentration ratio of CPV. [9]

Class of CPV	Typical concentration ratio
High Concentration PV (HCPV)	300-1000
Low Concentration PV (LCPV)	< 100

Figure 3.22 shows the growing of using concentrator PV along the past14 years.



From the figure above, the capacity installed increased rapidly until 2012 where the highest installed capacity was achieved, then the installed capacity decreased as no new companies investing in this industry and there are small companies growing rapidly in this industry. [9].

There are different technologies or devices used to focus the sun light. The most common technologies are as discussed below:

- Fresnel Lens:

  It consists of several sections of lenses with different angles to focus the light in a point or line. It provides less weight and less thickness in comparison with standard lens. It can be constructed in two shapes:

  - In a shape of a circle to provide a point focus with concentration ratios of around 500
  - In cylindrical shape to provide line focus with lower concentration ratios.

- Parabolic Mirrors:

All incoming parallel sun light (radiation) is reflected by the collector (the first mirror) through a focal point to a second mirror. Then, the second mirror, which is much smaller than the first mirror, reflects the light beams to the middle of the first parabolic mirror where the solar cell is located as it is shown in figure 3.23.

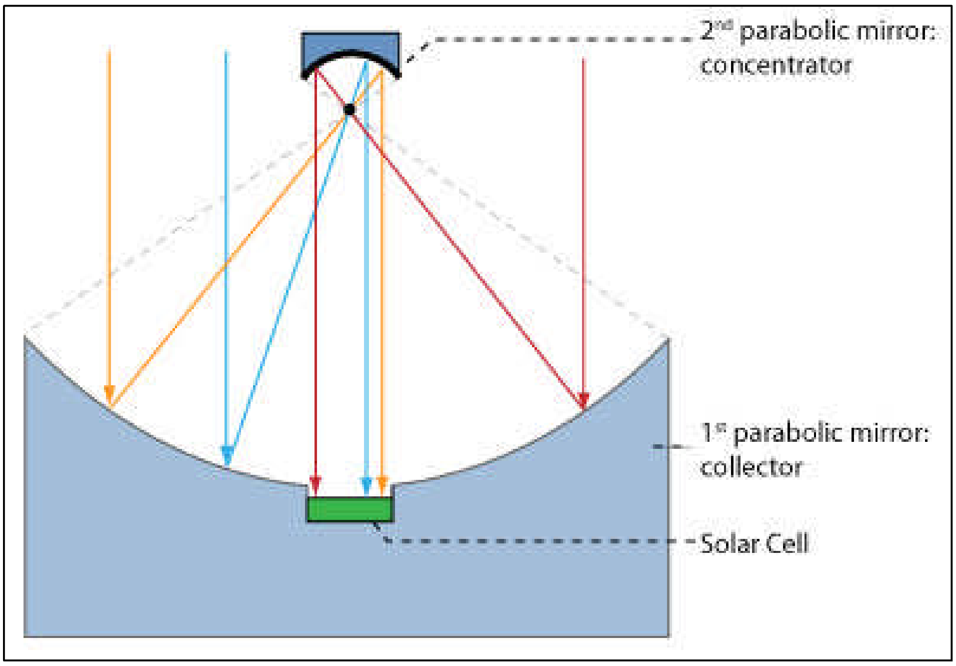


Figure (3.23): Parabolic Mirror

The main advantage of this configuration is that it doesn't use any optical lenses, and it can reach to concentration ratio of 500.

The cell temperature could reach more than 1000℃, at concentration ratio of about 500 [10], which is very high, so the cell should be cooled. Either by using an active cooling system which can cool the cells to about 100℃ [11], or by passive cooling using metal plates as a heat sink, In this method, the area of the heat sink increases linearly as a function of the concentration ratio, and it could cool the cell to about 40℃ [10].

- Reflectors:

  In reflectors, mirrors are used to concentrate the sunlight onto the solar cell. It is used for low concentration ratio.

- Luminescent Concentrators:

  A luminescent film is used to refract the sun light to the solar cell. It is a promising technology (under research). It doesn't require any optical lenses. Also, it doesn't require cooling. The film could be constructed so the wavelengths that cannot be converted to electric would just pass through. Hence, unwanted wavelengths would be removed.

  Concentrating the solar radiation on a small area of solar cell, will cause a huge increase in cell temperature. It could reach more than 1000℃ where this may destroy the cell, so cooling is required to prevent the failure of the cell.

  The cooling in concentrators is not an optional choice to increase the efficiency of the cells, but it is a mandatory option to protect the cell from broken.

3.4 summery

Temperature has a remarkable effect on the characteristics of the PV cell by affecting the characteristics of the silicon material itself. So, the rising in cell temperature directly affect the electric generation of the PV cell. As discussed in this chapter, the output of a PV module changes as a result of changes in its temperature and its efficiency may drop by about 4% once its temperature reaches about 70℃.

This temperature effect is magnified by using concentrator technology, and the temperature of the cell in these applications could reach more than 300℃. So the cooling of such system is a compulsory option to prevent PV cell failure.

CHAPTER FOUR
COOLING EFFECT

4.1. Introduction

The temperature has a remarkable effect on the performance (output power) of the PV panels as discussed in the previous chapter. In this chapter, the cooling methods and techniques will be discussed, exploring how each method works and affects the solar cells.

After that, this chapter will focus on the effect of cooling on the performance of the PV cell, to estimate the amount of improvement in the performance which can be achieved by keeping the cell temperature at a certain operating temperature, and how much power can be saved by cooling?

Finally, a case study will be considered to study the effect of cooling on applicable systems, and the economic feasibility of applying a cooling system on the PV panels in such systems.

4.2. Cooling methods

4.2.1. Passive cooling

They are called passive systems because they don’t need energy to operate. There are no moving parts or flowing fluids used in the cooling process, instead a special solid material used as a heat sink to cool the PV modules by conducting. So, no power or energy needed to cool the modules.

Usually ceramic is used in passive cooling, because it has high thermal conductivity, and can work as an electrical insulator.

Another form of passive cooling is to exploit the natural flowing of air. This can be achieved by distributing the modules in such way that can take advantage from the circulation of air between the modules. This idea may be applied in all systems – even those have a special cooling system- as it costs nothing and it depend on the wind speed in the site and on the distributing of the modules.

4.2.2. Active cooling

In active cooling, a special chosen cooling system is installed on the modules. To push air or water, on the back side or on the front panel of the module. Active cooling may use some energy from the PV system output or from other source.

Because there are a lot of configurations or modifications that can be installed on the PV modules to cool them, and it is hard to study all of them in this research, this chapter will focus on two configurations for cooling as study cases. The first one is cooling by cooled air at back side of the module. The second one is cooling by water at back side of the module.

4.3. Cooling effect on output power

In the previous chapter, the temperature effect on the output power of the PV module is discussed, and it is verified that the temperature has a remarkable effect on the output of the PV module. In this section, a cooling process will be installed (by simulation) on the PV module that was used in the previous analysis. This process is supposed to maintain the cell temperature at constant temperature (we will use 30℃ as desired cell temperature), and then the output will be compared with the output in normal case (without cooling, from the simulation in the previous chapter).

The efficiency difference between the two states (with and without cooling) will be calculated to measure the effect of cooling on the overall output of the PV panel.

Figure 4.1 shows the simulation results considering that the cell temperature is maintained at 30℃ by a cooling process.

The first part of the figure shows the open circuit voltage, it is founded to be almost constant (about 36.6 V) during the day. The second part shows the short circuit current and how it changes with solar radiation.

The third part shows the output power. The maximum can reach about 255 W, which is very close to the peak power of 250 W of this module. This little increase in maximum power occurred in very limited periods, and it is in the power tolerance range provided in the datasheet of the manufacturer.

The fourth part of the figure shows the difference between the cell temperature and the desired cell temperature (30℃). It shows the amount of temperature needed to be cooled at every hour during the year.

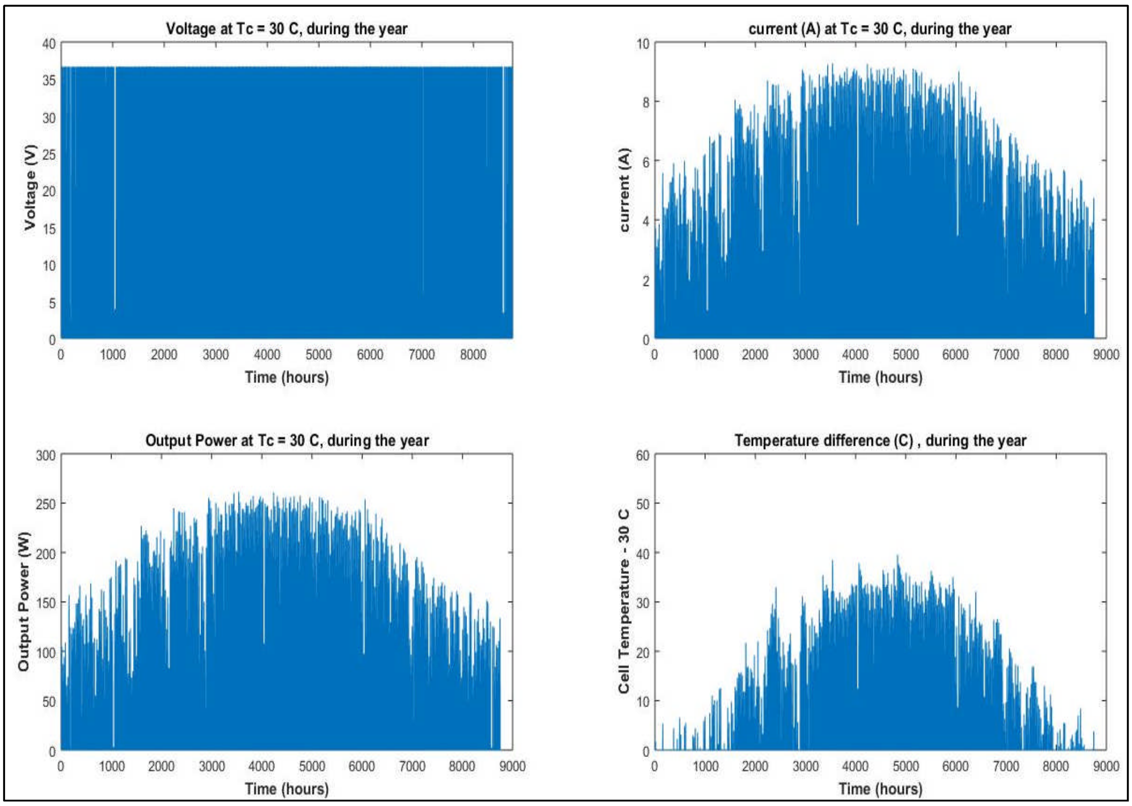


Figure (4.1): PV module output considering Tc = 30°C.

Figure 4.2 shows the output power clearly with scaling at some hours during the year to show how the power changes during the day and goes to zero in night hours.

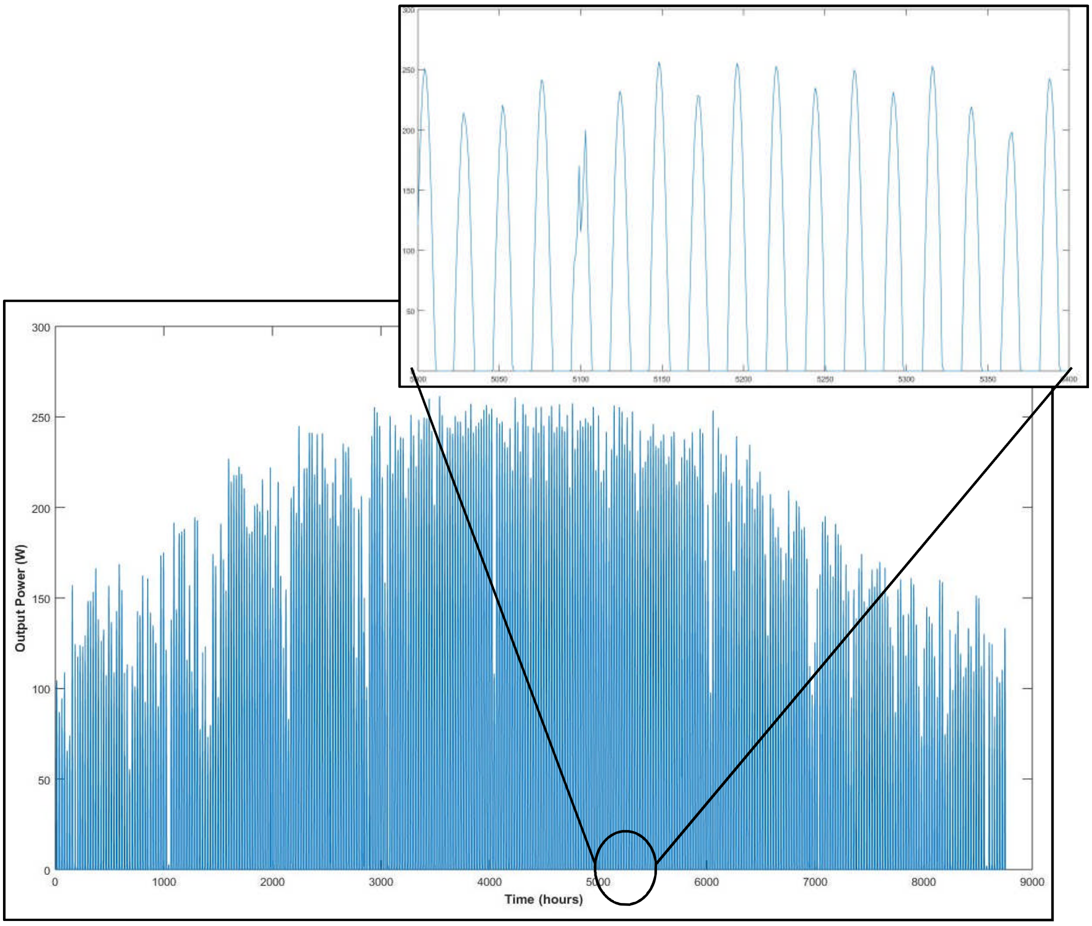


Figure (4.2): Output Power, scaling between hours of 5000 and 5500.

Now, the energy output generated during the year is calculated from the simulation and it is about 480 kWh/year which is more than the energy generated from the module without cooling which is about 331 kWh/year as in the previous chapter.

Calculating the efficiency of the module depending on the energy, with and without cooling can be done using the following equations:

$$\eta = \frac{\text{output energy}}{\text{input energy}} \times 100\% \qquad (4.1)$$

$$\text{Input energy} = E_{ann} \times \mathrm{A_m} \qquad (4.2)$$

Where:

η : Efficiency.

E_{ann}: solar radiation (annual average = 5.4 kWh/m^2-day, or measured radiation at each hour)

A_m: PV module area.

As the annual input and output energy are used to calculate the efficiency, the value of the calculated efficiency will represent the annual efficiency (the daily efficiencies could be more or less).

The input energy can be calculated using the equation 4.2, which uses the annual solar radiation (in Palestine) and the area of the module, or it can be calculated by the simulation program.

Using the annual solar radiation:

Input energy = 5.4 (kWh/m^2-day) * 1.49142 (m^2) * 365 (day) = 2939.6 kWh/year. (Input energy to the 250W module).

Using the simulation:

Input energy = the summation of the output power at all hours of the year = 2986.3 kWh/year. Which is very close to the input using the annual solar radiation.

Note that the programmed simulation software uses the same equation (4.2) but instead of using the annual solar radiation it uses the measured solar radiation at each hour during the year, so the simulation is done for 8670 hours.

Efficiency without cooling:

From the simulation result for the module at operating cell temperature (the normal operating status) - see section 4.2.3.3- the expected annual output energy from the module is about 331 kWh/year.

$$\eta = \frac{331\ \mathrm{kWh/year}}{2939.6\ \mathrm{kWh/year}} \times 100\% \approx 11.26\ \%$$

Efficiency with cooling (T_c = 30℃):

From the simulation done for T_c = 30℃, the expected annual output energy is about 480 kWh/year

$$\eta = \frac{480\ \mathrm{kWh/year}}{2939.6\ \mathrm{kWh/year}} \times 100\% \approx 16.3\ \%$$

So, cooling the module and maintaining its temperature at 30℃ increases the efficiency by about 5%, in other words, cooling the module will save about 130 kWh/year.

In addition to saving output energy, this increase in efficiency will save space required for the same output energy. This means reduction in the area of the PV system required to produce the same energy. For this module, the area required to produce the 331 kWh/year is about 1.49142 m^2 (as mentioned in the manufacturer datasheet), but if a cooling system installed in the module to maintain its temperature at 30℃, the area required to produce the same amount of energy (331 kWh/year) will be about 1.1 m^2. So cooling will save also about 0.4 m^2 per module. (The area is roughly calculated by reversing the simulation).

4.4. Study case: HVAC system powered by cooled PV system.

In this section, a case study will consider the effect of cooling on a real (simulated) system. The case here is to power HVAC system at certain capacity by a PV system, and cool this PV system through special line comes from the same HVAC system.

After the PV system is designed, and the required PV capacity is known (the capacity required to power the HVAC system without cooling the PV modules). Then a simulation program will be executed to simulate the cooling process and expecting how this cooling will affect the performance of the system (PV)? And how much will be saved?

Let’s suppose that, the space wanted to be air-conditioned needs about 1 ton refrigeration, which is equivalent to about 3.52 kW. 1 ton refrigeration split unit supposed to be used, the input power required to run this unit can be calculated using the required coefficient of performance of the system, or simply be choosing a common split unit conditioner in Palestine market which could be from “Midea” company. The chosen model is with capacity of 3.52 kW. Its datasheet can be found in appendix B.

4.4.1. The PV system with and without cooling

Now, the designing of the PV system done as following:

From the split unit datasheet, the required input is 1760 W (at full capacity), suppose that the air conditioner will work for 8 hours per day, so the required energy is: 14080 Wh/day.

$$\text{PV Peak load capacity} = \frac{\text{Energy per day}}{\text{Peak sun hours (PSH)per day}} \quad [5] \qquad (4.3)$$

The peak sun hours in Palestine is about 5.4 hours [5].

$$\text{PV peak load} = \frac{14080}{5.4} = 2607\ \text{W}$$

We need a PV system with capacity of about 2607 W ≈ 2.6 kW

By selecting the same PV module which all the simulations in this research are based on, the 250 W Hanwha module, the number of required panels is:

$$\text{Number of modules (panels)} = \frac{\text{Total capacity}}{\text{The Output of 1 module}} = \frac{2607}{250} = 10.4$$

So, we need about 11 modules, 250 W each.

Note that the designing of full PV system (with batteries, inverter, regulator and charger) will not be discussed in this research, as it is studying the effect of cooling on the output from the PV modules, so all we need to now here is the number of modules in the system which is founded to be 11 modules.

The energy needed per year by the air conditioner is about 5.14 MWh/year. And the expected energy output from the PV system is about 5.4 MWh/year, which seems to be more than enough to run the air conditioner, but the simulation results (which simulate the real situation) say something else. Figure 4.3 shows the simulation results for this PV system during 1 year. By considering the efficiency of the inverter, regulator and charger is about 0.95% [1].

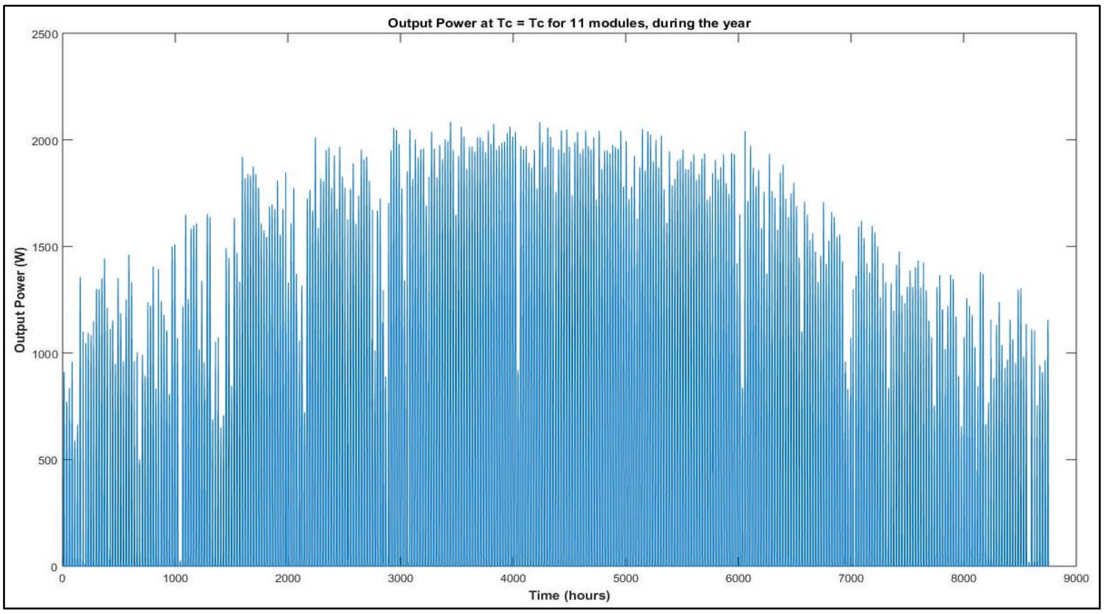


Figure (4.3): The output of PV system contain 11 modules without cooling.

Because the drop in voltage with cell temperature increases, the simulation expect that the maximum power can be produced from the system is about 2083 W, and the total produced energy by the PV system will be about 4 MWh/year, which is less by about 1 MWh/year from the expected output from the PV system. Note that, this does not mean that the system will not be able to run the air conditioner, but the total energy produced during the year will not be enough to run the air conditioner 8 hours per day.

Now, by installing a cooling system to cool the PV modules (to maintain the modules temperature at about 30℃), the output power will be as in shown in figure 4.4. By considering the efficiency of the inverter, regulator and charger is about 0.95% [1].

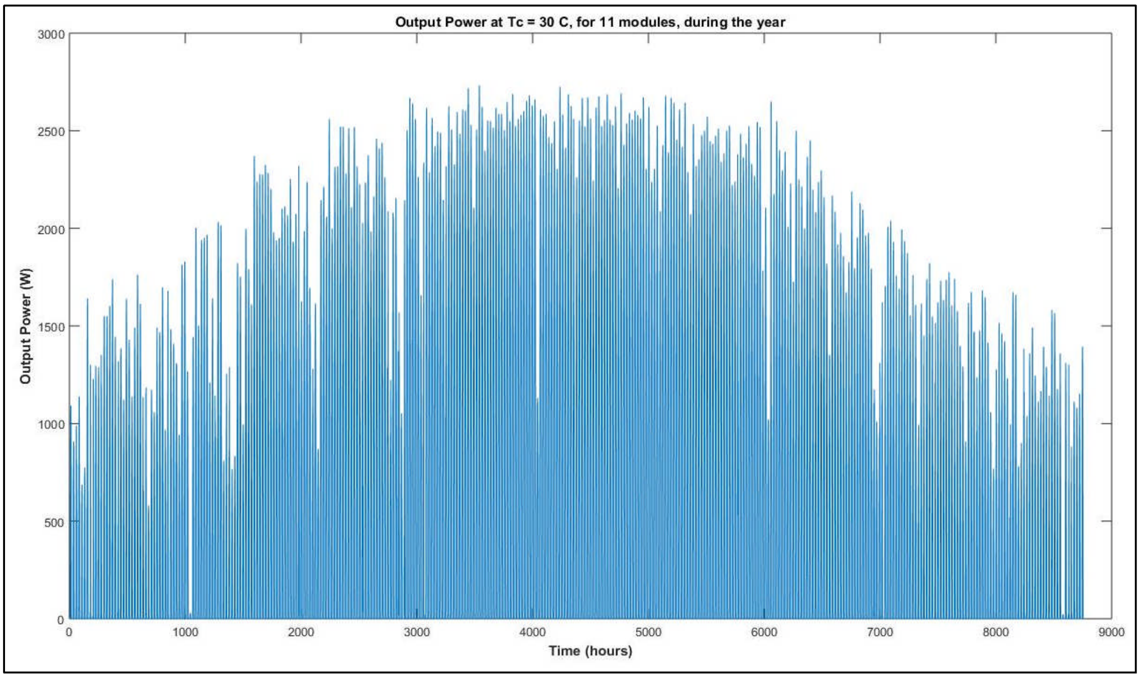


Figure (4.4): The output of PV system contain 11 modules with cooling to Tc = 30℃.

The maximum output power is about 2732 W, and the total produced energy during the year is about 5 MWh/year, which is almost the same as the required energy to run the air conditioner 8 hours per day for 1 year.

This means, if the PV system without cooling is used, an extra 1 MWh/year will be needed. This extra amount can be compensated from the grid (if the system is ON-Grid system), or by adding extra modules to the system. But if a cooled PV system is used, no extra energy will be needed.

It is found that, by simulation, 4 modules must be added to the system to compensate the lost in output due to cell temperature increase.

4.4.2. Cost analysis

We can say that there are three options to compensate the lost energy, the first one is the grid, second one is adding 4 modules and the third one is cooling the existing PV system.

From Grid:

Compensating the needed energy from the grid will cost as following: (considering that the system is ON-Grid system).

The price of 1 kWh in local town (in Palestine) is about 0.6 NIS [12].

We need an extra 1 MWh/year, this will cost: $1000 \times 0.6 = 600$ NIS/year.

This choice will cost about 600 NIS yearly.

Adding 4 modules:

Adding four modules will add an extra investment cost to the system, with yearly maintenance cost.

The cost of 4 modules, 250 W each is about 5200 NIS (this cost is based on the market prices in Palestine).

Yearly maintenance cost: 4 modules, each 250 W, means 1 kW system, the maintenance cost of 1 kW is about = 13 $/kW/year (48 NIS/kW/year) as a thumb rule. (This cost include cleaning PV modules, checking connections and other periodic tasks).

Cooling the PV system:

First the cooled space must be calculated to know how much refrigeration capacity is needed:

11 modules, each has area 1.49142 m^2, total area is 11 * 1.49142 = 16.4 m^2.

An air duct added to the back side of the module, to act as an air channel flow. As described in figure 4.5:

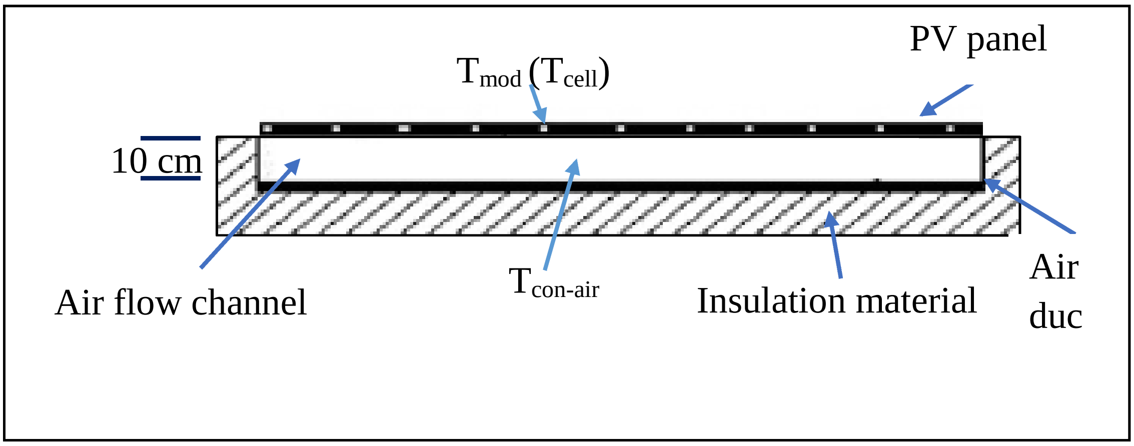


Figure (4.5): Cooling duct configuration.

From the figure, the area of the duct is the same as the area of the module, and the height is 10 cm (0.1 m), the space inside the air duct and the back side of the module is the space wanted to be cooled, and it is about 0.149142 m^3 for each module.

Since the cooled space behind each module is 0.149142 m^3, the total cooled area is 16.4 m^2 and the volume is 1.64 m^3. This space needs about 0.04 ton refrigeration. This is very small refrigeration capacity compared to the total refrigeration capacity we have (1 ton), so practically adding this small space to the cooled space (room) will not affect the efficiency or operation of the air conditioner. As a result, we can use the same air conditioner to cool the PV modules without affecting the cooling of the room. And a temperature controller should be used to control the temperature in the air flow channel.

The cost of the insulated duct installed at the back side of the module is about 2000 NIS. Note that the estimation of the cost based on the prices in the local market. (As we got some prices from some HVAC companies).

Now, the cost of installing a cooling system on the 11 modules is about 2000 NIS, with some maintenance cost.

The maintenance cost couldn't be estimated as we couldn't get any prices for maintenance procedure from the local companies, but we can suppose that, the maintenance cost for the cooling system is same as the maintenance cost for the extra modules in adding modules option.

Some valves and other accessories needed to be added to complete the system and their cost is about 400 NIS. (Based on local market).

The total cost of the cooling system is about 2400 NIS.

Comparing the three options, adding modules is the most expensive option. Connecting to grid could be the cheapest option for short periods, as the cost for this option is annually. Simply and directly, the payback period for installing a cooling system – comparing to connecting to grid- is about 4 years, it is calculated by dividing the cost of cooling system on the annual cost of connecting to grid. $\left(\frac{2400}{600} = 4\right)$.

Finally, a payback period of 4 years considered to be feasible in economic studies. And we can say that applying a cooling system on such PV systems could be a feasible option.

4.5. Summary

Cooling the PV modules saves some energy, and enhance the performance of the modules. It may be economically feasible in some cases.

There are different methods and techniques that can be used for cooling PV modules. Choosing one of the methods depends on many parameters. But there are some ideas of cooling which have no cost and can affect the performance of PV such as distributing the modules in a layout to make benefit from air circulation.

Installing a cooling system on a PV system used to supply an air conditioner may return its cost by 4 years, which is not long period considering that the normal payback period for any PV system is from 4 to 7 years.

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

In this study, the temperature effect on the PV cells was discussed and a simulation to measure this effect was performed. A simulation was also performed to measure how cooling PV modules could be effective and feasible. The MATLAB program was used to accomplish the simulation.

The temperature affects the internal characteristics of the silicon material, as all semiconductor materials are sensitive to temperature change. Increasing temperature reduces the band gap of the semiconductor. This leads to decrease the bond energy. These changes directly affect the open circuit voltage of the cell.

Increasing the solar radiation intensity on the PV cell will increase the short circuit current, but it also increases the cell temperature. The relation between solar radiation and PV cell temperature was verified based on real measurements done at an installed system in Jericho.

2.2 mV per℃-cell is the decrement in open circuit voltage for silicon, and using the simulation, about 5% losses in the total efficiency of a PV module was measured, from about 16.3% at cell temperature of 25℃ to about 11.2% at 70℃. And 5 volt decrement in the voltage was measured.

In concentrator technology, high cell temperature could be reached. It may reach to about 1000℃ (without cooling). So the concentrated cells should be cooled to protect them from high temperature.

Cooling PV modules could save about 5% of the total yearly efficiency, measured based on the yearly output from the PV module that cooled to 30℃

cell temperature. Cooling could also decrease the required installation area for a certain capacity.

Finally, cooling the PV modules could be effective and feasible if it is applied on large plants. But in these days, cooling PV is used with concentrators not with flat PV modules, which is still under researching and studying as a lab idea.

5.2. Recommendations

Considering the measurements and results of this study, the following points are recommended for future work:

- Applying a cooling system on a real PV system and experimentally measuring the effect of cooling on it.
- Studying the possibility to apply cooling on large scale (MW) plants, which can save space and power.
- Applying the Co-generation principle by employing the heat generated from the PV modules to other applications especially for concentrated solar cells.
- Study the possibility to use special passive coolants, which can convert heat to other forms of energy.

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APPENDICES

Appendix A: Hanwha solar Panel data sheet.

SF220 Poly

Polycrystalline Solar Module

OVERVIEW

Hanwha SolarOne's SF220 Polycrystalline Module delivers the performance and efficiency required for large power ouput applications. Featuring a smooth, all-blue surface and a tight ±3% power tolerance, the SF220 Poly provides an aesthetically attractive and efficient option for commercial and utility installations. The module has undergone comprehensive testing for reliable performance over time and is certified to comply with the latest Class A safety standards.

KEY TECHNICAL FEATURES

- 5 year product warranty, 25 year performance warranty*
- Module certified to withstand high snow loads, up to 5.4kN/m^2**
- Tight power tolerance: ±3%, anti-reflective coating
- Free module recycling through membership in PV Cycle

*Please refer to Hanwha SolarOne Product Warranty for details.
**Please refer to Hanwha SolarOne module Installation Guide.

QUALITY AND ENVIRONMENTAL CERTIFICATES

- ISO 9001 quality standards and ISO 14001 environmental standards
- OHSAS 18001 occupational health and safety standards
- IEC 61215 and IEC 61730 Class A certifications
- Conformity to CE

ABOUT HANWHA SOLARONE

Hanwha SolarOne is a vertically integrated manufacturer of photovoltaic modules designed to meet the demands of the global energy consumer. From high-grade crystalline silicon, to module production, to project development and financing, Hanwha SolarOne is setting the new standard in innovation and value.

- High reliability, guaranteed quality, and excellent cost-efficiency due to vertically integrated production and control of the supply chain;
- Optimization of product performance and manufacturing processes through a strong commitment to research and development;
- Global presence throughout Europe, North America, and Asia, offering regional technical and sales support.

TÜV CE IEC PV CYCLE

Hanwha SolarOne

www.hanwha-solarone.com

ELECTRICAL CHARACTERISTICS

Electrical Characteristics at Standard Test Conditions (STC)

MAXIMUM POWER (P_{max})	225W	230W	235W	240W	245W	250W
OPEN CIRCUIT VOLTAGE (V_{oc})	36.7V	36.8V	36.8V	37.0V	37.1V	37.2V
SHORT CIRCUIT CURRENT (I_{sc})	8.18A	8.34A	8.44A	8.54A	8.64A	8.74A
VOLTAGE AT MAXIMUM POWER (V_{mp})	29.9V	30.0V	30.1V	30.2V	30.3V	30.4V
CURRENT AT MAXIMUM POWER (I_{mp})	7.53A	7.67A	7.81A	7.95A	8.08A	8.22A
MODULE EFFICIENCY (%)	13.6	13.9	14.2	14.5	14.8	15.1

P_{max}, V_{oc}, I_{sc}, V_{mp} and I_{mp} tested at STC defined as irradiance of 1000W/m² at AM 1.5G solar spectrum and temperature 25 ±2°C.
Power tolerance of ±3% refers to measured performance.

Electrical Characteristics at Normal Operating Cell Temperature (NOCT)

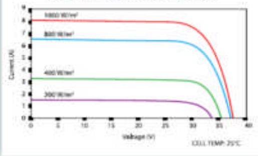
MAXIMUM POWER (P_{max})	163W	167W	170W	174W	178W	182W
OPEN CIRCUIT VOLTAGE (V_{oc})	33.1V	33.3V	33.5V	33.7V	34.1V	34.2V
SHORT CIRCUIT CURRENT (I_{sc})	6.50A	6.66A	6.74A	6.84A	6.99A	7.07A
VOLTAGE AT MAXIMUM POWER (V_{mp})	27.1V	27.2V	27.3V	27.4V	27.6V	27.7V
CURRENT AT MAXIMUM POWER (I_{mp})	6.02A	6.14A	6.23A	6.35A	6.46A	6.58A
MODULE EFFICIENCY (%)	12.3	12.6	12.9	13.2	13.5	13.8

P_{max}, V_{oc}, I_{sc}, V_{mp} and I_{mp} tested at STC defined as irradiance of 1000W/m² at AM 1.5G solar spectrum and temperature 25 ±2°C.
Power tolerance of ±3% refers to measured performance.

Performance at Low Irradiance:

The typical relative change in module efficiency at an irradiance of 200W/m² in relation to 1000Wm² (both at 25°C and AM 1.5G spectrum) is less than 5%.

Various Irradiance Levels



Temperature Characteristics

NORMAL OPERATING CELL TEMPERATURE (NOCT)	45 ±3°C
TEMPERATURE COEFFICIENTS OF P	-0.45%/°C
TEMPERATURE COEFFICIENTS OF V	-0.32%/°C
TEMPERATURE COEFFICIENTS OF I	-0.04%/°C

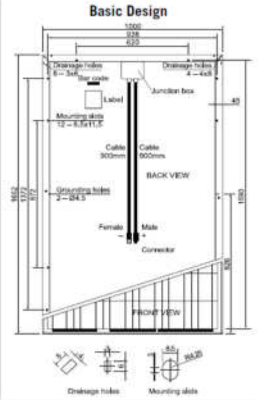
Maximum Ratings

MAXIMUM SYSTEM VOLTAGE	1000V (IEC); 600V (UL)
SERIES FUSE RATING	15A
MAXIMUM REVERSE CURRENT	Series fuse rating multiplied by 1.35

MECHANICAL CHARACTERISTICS

DIMENSIONS	1652mm x 1000mm x 45mm (65.04 in x 39.37 in x 1.77 in)
WEIGHT	21kg (46.2 lbs)
FRAME	Aluminum alloy
FRONT	Tempered glass
ENCAPSULANT	EVA
BACK COVER	Composite sheet
CELL TECHNOLOGY	Polycrystalline
CELL SIZE	156mm x 156mm (6.14 in x 6.14 in)
NUMBER OF CELLS (Pieces)	60 (6 x 10)
JUNCTION BOX	Protection class IP65 with bypass-diode
OUTPUT CABLES	Solar cable: 4mm²; length 900mm (35.4 in)
CONNECTOR	Linyang LY0706-2

Basic Design



SYSTEM DESIGN

OPERATING TEMPERATURE	-40°C to 85°C
HAIL SAFETY IMPACT VELOCITY	25mm at 23m/s
FIRE SAFETY CLASSIFICATION	Class C
STATIC LOAD WIND/SNOW	5.4kN/m²

PACKAGING AND STORAGE

STORAGE TEMPERATURE	-40°C to 85°C
PACKAGING CONFIGURATION	22 pcs per pallet
LOADING CAPACITY (40 FT. CONTAINER)	572 pieces

Hanwha SolarOne

www.hanwha-solarone.com

Appendix B: Midea Air conditioner data sheet.

Tropical Inverter, Powerful Cooling Even with 60°C Outdoor Temperature

The advanced tropical compressor is designed to withstand the most extreme weather conditions. You can enjoy comfortable and cooling air even when the outdoor temperature is as high as 60°C.

iECO Mode, Save Energy by 60%

The air conditioner is equipped with the iECO energy-saving technology, which perfectly synergized with highly efficient frequency conversion system. You can indulge in comfortable coolness while saving 60% power over 8 hours.

Model	Indoor Unit		MSMBAU-09HRFN1-QRD0GW(B)	MSMBBU-12HRFN1-QRD0GW(B)	MSMBCU-18HRFN1-QRD0GW(B)	MSMBDU-24HRFN1-QRD0GW(B)
	Outdoor Unit		MOBA02-09HFN1-QRD0GW	MOB03-12HFN1-QRD0GW	MOB02-18HFN1-QRD0GW	MOCA01-24HFN1-QRD0GW
Power Supply		V/Ø/Hz	220-240 / 1 / 50	220-240 / 1 / 50	220-240 / 1 / 50	220-240 / 1 / 50
Capacity	Cooling	kW	2,64 (1,17 - 3,31)	3,52 (1,35 - 4,51)	5,28 (1,90 - 6,18)	7,03 (2,58 - 8,09)
	Heating	kW	2.93 (0,91 - 3,75)	3,81 (1,08 - 4,92)	5,57 (1,44 - 6,80)	7,62 (2,08 - 9,29)
Power Input	Cooling / Heating	kW	0,100 - 1,270 / 0,140 - 1,340	0,110 - 1,740 / 0,160 - 1,760	0,150 - 2,380 / 0,220 - 2,430	0,230 - 3,110 / 0,310 - 3,320
SEER	Cooling	W/W	6,80	7,20	6,80	6,20
SCOP (2°C)	Heating	W/W	5,10	5,30	5,40	5,10
Energy Efficiency Class	Cooling		A++	A++	A++	A++
	Heating		A+++	A+++	A+++	A+++
Running Current	Cooling / Heating	A	0,4 - 5,5 / 0,6 - 5,8	0,5 - 7,6 / 0,7 - 7,7	0,7 - 10,3 / 1,0 - 10,6	1,0 - 13,5 / 1,3 - 14,4
Sound Pressure (indoor unit)		dB(A)	37 / 31 / 23	38 / 35 / 28	42 / 37 / 33 /	46 / 40 / 30
Sound Pressure (outdoor unit)		dB(A)	54	54	54	60
Dimentions W x D x H Weight	Indoor Unit	mm	730x198x293	810x200x300	980x225x325	1090x235x338
		kg	7,4	8,2	10,5	12,9
	Outdoor Unit	mm	770x300x555	800x333x554	800x333x554	845x363x702
		kg	27,1	29,7	37,2	48,5
Refrigerant piping (liquid / gas)		mm	6,35 / 9,52	6,35 / 9,52	6,35 / 12,7	9,52 / 15,9
Max. refrigerant pipe length		m	25	25	30	50
Max. difference in level		m	10	10	20	25
Operation Temperature	Cooling	°C	-15 ~ 60	-15 ~ 60	-15 ~ 60	-15 ~ 60
	Heating	°C	-15 ~ 30	-20 ~ 30	-20 ~ 30	-20 ~ 30
Refrigerant			R410A	R410A	R410A	R410A

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تحسين أداء الخلايا الشمسية بواسطة أنظمة التبريد والجدوى الاقتصادية لتطبيقها على أنظمة الخلايا الشمسية ذات القدرة العالية.

إعداد
أحمد عودة

إشرف
أ.د. مروان محمود

قدمت هذه الاطروحة استكمالا لمتطلبات الحصول على درجة الماجستير في الطاقة النظيفة واستراتيجيات ترشيد الاستهلاك، كلية االدراسات العليا، جامعة النجاح الوطنية، نابلس، فلسطين.

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إعداد

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إشراف

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ملخص

من المعلوم ان درجة حرارة الخلايا الشمسية تؤثر سلبيا بشكل ملحوظ على كفائة هذه الخلايا، وتركز هذه الدراسة على قياس هذا التأثير وتحاول اثبات جدوى تبريد انظمة الخلايا الشمسة.

ارتفاع درجة حرارة الخلية الشمسية يسبب بعض التغيرات في خصائص المادة شبه الموصلة (عادة السيليكون) التي تستخدم في تصنيع الخلايا الشمسية، مما يؤدي الى تقليل جهد الدائرة المفتوحة لهذه الخلية، وبالنتيجة تقليل القدرة المولدة و كفائتها.

من خلال قراءات تم قياسها على نظام خلايا شمسية مركب في فلسطين، وجد ان حرارة الخلية قد تصل تقريبا الى 70 درجة مئوية، في ظروف التشغيل الطبيعية، وهذه القيمة اعلى من درجة حرارة الخلايا تحت ظروف التشغيل القياسية (STC) بثلاث مرات. و يؤدي هذا الى فقدان حوالي 5% من كفائة الخلايا المركبة تحت نفس الظروف الجوية.

بهدف محاكاة عمل لوحة خلايا شمسية في فلسطين لمدة سنة كاملة (بالاعتماد على درجات الحرارة في فلسطين) ، تم تصميم برنامج محاكاة لدراسة التغيرات في كفاءة الخلايا عند درجات حرارة مختلفة. ان تبريد الخلايا الشمسية وتثبيت حرارتها عند 30 درجة مئوية سوف يمنع انخفاض جهد الدائرة المفتوحة للخلية بمقدار 4 V ، و يؤدي للحفاظ على 4% من كفائة الخلايا السنوية تقريبا، التي سيتم فقدانها عند تشغيل الخلايا دون تبريدها.

لقد وجد ان تطبيق نظام تبريد على الخلايا الشمسية قد يكون مجدي، بمحاكاة هذا التطبيق على نظام خاص، حيث ان فترة استرداد رأس المال (Payback period) هي 4 سنوات تقريبا و تعتبر هذه فترة مقبولة.

اما في نظام المركزات الشمسية (solar concentrators) فإن درجة حرارة الخلايا قد تصل الى حوالي 1000 درجة مئوية لذا فان تبريد هذه الخلايا هو خيار الزامي لمنع تلف الخلايا