Development of Photovoltaic Modules and System Performance under Different Climate Conditions in Iraq

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SUMMARY

A growing demand for energy, the security of supply of fossil resources and the international agreements to mitigate climate change are key issues of modern society. These developments drastically increased the necessity of large scale implementation of renewable energy technologies over the past two decennia and will continue to do so in the near future. This research compares and analyses the performance of various PV modules (several thin-film technologies as well as several crystalline silicon wafer based technologies) in the tropics by conducting comprehensive indoor measurements and outdoor monitoring tests. A thorough study of the modules and strings, spectral responses is performed, revealing that the blue-shifted spectrum in the tropics causes significant differences in the module performance. Based on outdoor testing data, a model is derived to extract the temperature coefficients of the modules' maximum power points and to understand their dependence on irradiance and module temperature. Module degradation rates are found to be relatively high compared to temperate climates. A comparison of measured and simulated results were done. Finally, 'Tropical Test Conditions' are defined, which enable a standardized performance comparison across different PV module technologies in tropical regions.

1. INTRODUCTION

In the 21th century, energy use and resources have become a major issue. This is even tougher in the Iraqi regions, one of the first producers of oil in the world, and also a high consumer. Air conditioning is a huge part of the consumption. On top that, no renewable energy is used at the moment in the region. [1]

Traditionally, solar energy has been divided into two distinct but separate fields of study: solar thermal, where incoming radiation is converted into heat, and photovoltaics (PV), where solar energy is converted to electricity. Solar thermal systems have long been used for applications such as water heating, space heating and power generation. Photovoltaics, although a comparatively recent development, have also been applied to a large number of electricity generating applications, including watches, calculators and large power systems such as those used at many places. [2]

Among the different renewable energies, solar energy is by far the most abundant and available virtually everywhere. The effect of generation of voltage or electric current in a material upon exposure to light is called photovoltaics (PV) [2]. The application of PV modules has seen a massive growth since the 2000s. This development is expected to continue at a smaller growth rate, however now from a higher level (as in fig.1).

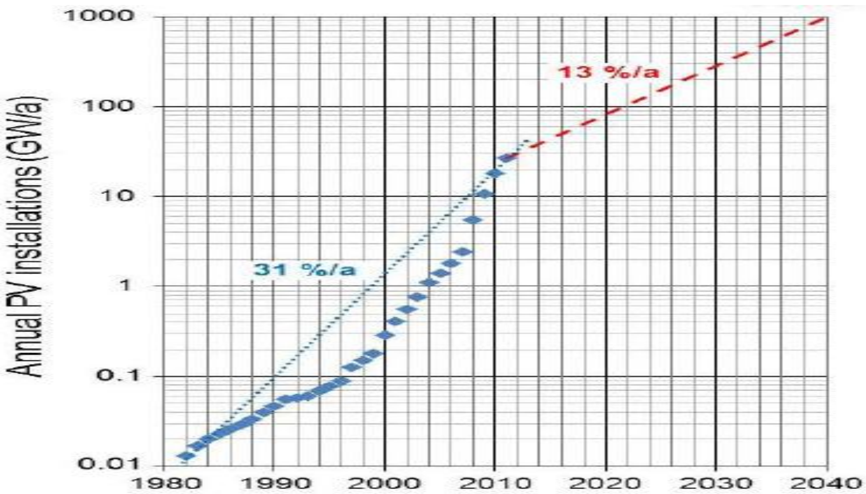

Fig.(1) Historic and expected development of the global solar PV production [3].

The high demand of energy has raised social, political, and economic challenges, which call for sustainable solutions. Renewable energy has thus been given more attention and grown continuously in this region. Given the rapid decreases in the cost of solar panels in the past several years, solar electricity has become cost-competitive with traditional energy from the grid in some countries, reaching the so-called "grid parity" for larger roof-top systems [4]. The performance and reliability of PV modules depends on the operating conditions. It is therefore important to fill the knowledge gap on PV module performance in the tropics. This information can provide constructive advice to manufacturers to produce PV modules optimized for the tropical climates and is also desirable for system integrators and investors to easily determine which type of PV module techno-logy gives the best performance at the given conditions in the tropics.

1.1 Current status of PV module technologies:

Among all the technologies in the PV market, wafer-based crystalline silicon ("c-Si") is so far the most developed material for PV cells and modules, and huge achievements have been reached in improving its costs and conversion efficiencies [4]. The market share of monocrystalline silicon (mono c-Si) and multicrystalline silicon (multi c-Si) together was over 90% at the end of 2013 [5]. The multicrystalline Si technology itself accounts for 62% of all modules produced. Although thin-film modules comprise less than 10% of the global PV market, the production keeps growing due to the overall growth of the industry. The major materials for thin-film PV modules are (1) amorphous silicon ("a-Si"), (2) microcrystalline silicon ("μc-Si"), (3) Cadmium telluride ("CdTe"), and (4) Copper indium gallium diselenide ("CIGS"). Figure (2) shows the expected production capacities of thin-film materials until 2015 [6].

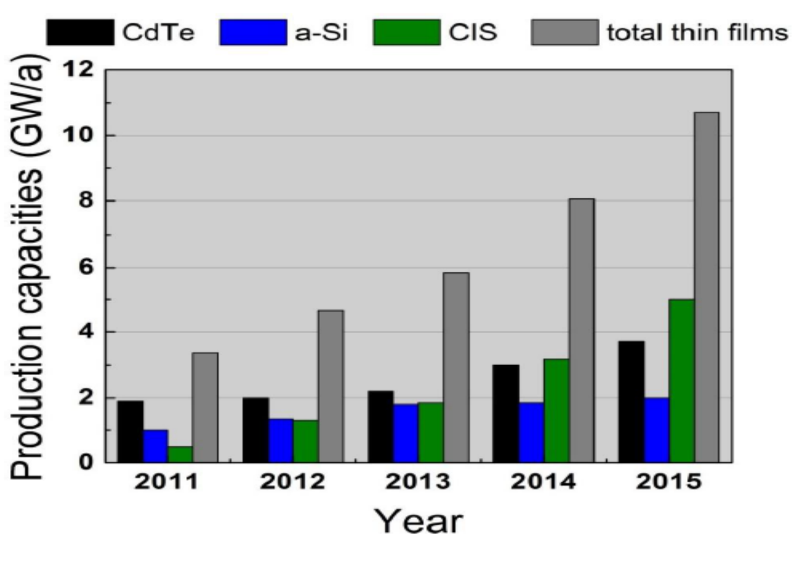

Fig.(2) Production capacities of thin-film PV module for CdTe, a-Si/μc-Si and CIGS [6].

1.2 Characteristics of various PV module technologies:

Crystalline Si refers to both monocrystalline Si (mono c-Si) and multi-crystalline Si (multi c-Si), depending on the presence of grain boundaries in the Si. Monocrystalline Si is also often called “single-crystal” Si. Various approaches have been devised to enhance the conversion efficiency of c-Si solar cells. To improve the c-Si cell efficiency, high-carrier-lifetime substrates are usually required, Amorphous Si (a-Si) PV modules have been in commercial production since 1980 [7]. The production of a-Si requires only about 1% of the silicon that would have been used to produce a c-Si based solar cell, so in theory they should be much cheaper than c-Si based solar cells [38].

Adding germanium (Ge) to the silicon can reduce the bandgap of the amorphous material, thus enabling the double- ('tandem') or triple-junction (e.g., a-Si/a-Si/a-SiGe) solar cells. The world-record efficiency for CdTe solar cells and modules to date are 19.6% and 16.1%, respectively [7], held by First Solar, the most successful company producing commercial CdTe modules. CdTe is, in principle, one of the best-suited materials for photovoltaics with its direct bandgap of 1.44 eV, close to the optimum for solar conversion [8]. In 2013, a CIGS solar cell with a new record efficiency of 20.4% was achieved on flexible polymer foils [9].

1.3 PV module power rating and outdoor performance indicator:

The current internationally accepted standard test conditions specify 25°C module temperature, solar spectrum, and a solar irradiance intensity of 1000 W/m2 for power measurements of terrestrial non-concentrating ('flat-plate') PV devices.
The "Performance Ratio" , relating the outdoor performance with the measured efficiency, is widely applied as a gauge to evaluate the relative merits of PV installations of different sizes, locations, technologies, and climates.
Typical values of the performance ratio of PV systems are reported to be in the 70 - 90 % range [10].

1.4 Environmental factors affecting the module performance:

The irradiance intensity incident on a PV module in the field is not constant, and may only reach 1000 W/m2 around solar noon. Ideally, the power output of a solar panel is proportional to the incident irradiance since the photo-current is proportional to the irradiance [11].

The module temperature is one of the most important parameters affecting the power output of PV modules. The efficiency of c-Si modules decreases with increasing temperature, while thin-film modules show a less predictable trend, with additional dependence on the operating histories [12]. for thin-film modules with very thin absorber layer, large incidence angles caused by diffuse light can lead to longer optical path length in the solar cells and therefore better light absorption [13].

1.5 Considerations for PV modules operating in the world:

Although PV has been widely applied and studied in temperate climates, very little scientific work has been carried out on how the modules perform in many regions. Literature studies indicate that the performance of PV modules is very location dependent [14], and specifically is a function of the operating conditions and environmental factors such as irradiance intensity and spectrum, ambient temperature, and humidity.

2. STUDY OF THE SPECTRAL RESPONSE OF FULL-SIZED PV MODULES:

The spectral response measurement of PV modules has a higher complexity, owing to the fact that they consist of series-connected cells, which may have different spectral responses and often are additionally connected to bypass diodes. Complications arise because (1) the series interconnection itself will influence the measurement, and (2) there is to date no steady-state high-intensity monochromatic light source available for full-area module illumination. PV module, such as a single-junction a-Si module, usually consists of more than 100 solar cells connected in series without bypass diodes. The shunt resistances RShunt within a thin-film module are usually much smaller (half or less) compared to those of wafer-based modules [15,16].

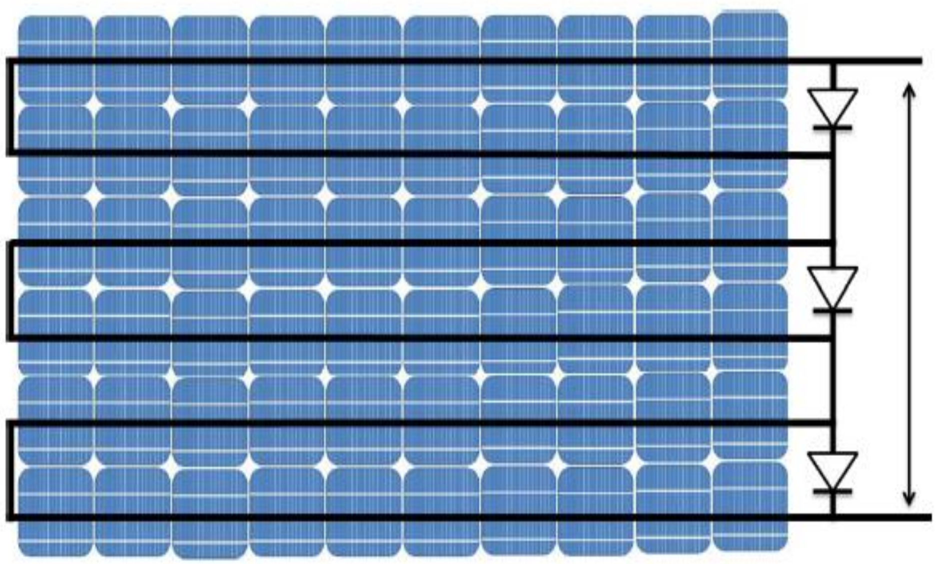

Fig.(3) Sketch of a typical silicon wafer-based c-Si module

Thus in the simulation study, a silicon wafer-based module (exhibiting higher RShunt values than thin-film modules) was chosen.

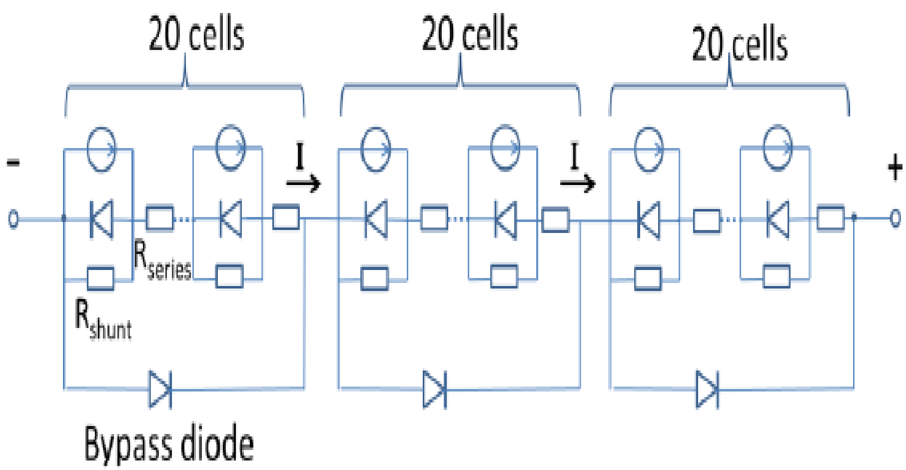

Fig.(4) Sketch of the circuit simulation model of a silicon wafer-based PV module based on the one-diode model.

In order to test how the individual cell spectral responses, their shunt resistances and the bypass diodes influence the spectral response of a PV module, circuit modeling using the simulation software was conducted [16]. The corresponding circuit model of a wafer-based PV module is shown in figure (4). The circuit model is based on the one-diode model describing the individual cells within the module, including a current source, a shunt resistance and a series resistance. The reverse saturation current for all cells is set to $1x10^{-10}$ A and the cell area is assumed to be 156 mm × 156 mm. As cells are connected in series, variation of the series resistance of individual cells can be accumulated as a lumped series resistance of the whole module and will not affect the module solar ratio. [17]

3. RESULTS:

3.1 Individual Modules:

The performance ratio comparison across different technologies based on standard test conditions therefore leads to inconclusive results, even though they are part of an identical measurement setup (as in fig. 5).

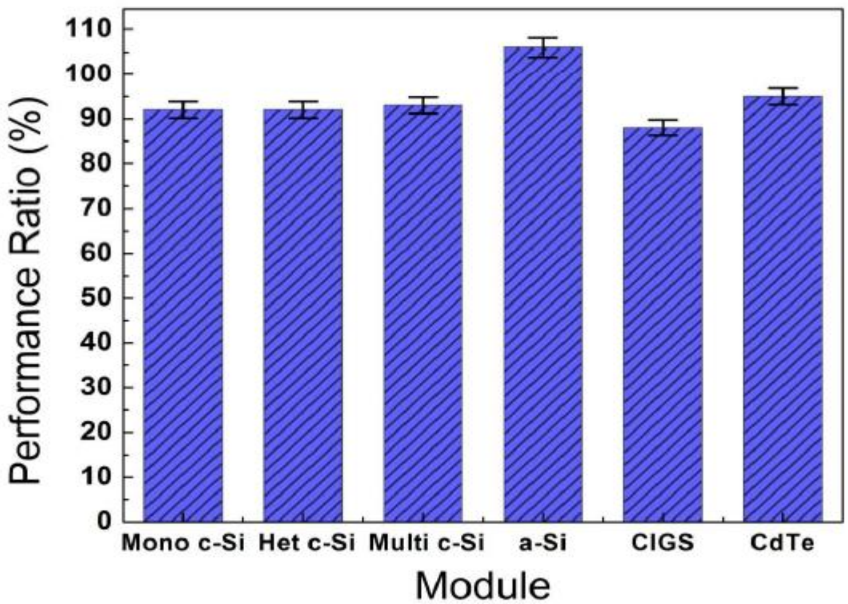

Fig.(5) DC performance ratio based on the power for individual modules.

Hence, it would be desirable to have a set of test conditions which can be used for either indoor or outdoor measurements and reflect the tropical PV module working conditions, to enable a standardized performance comparison across different PV technologies under these conditions.

The distribution of solar radiation peaks at irradiance between 700 to 900 W/m2 and contains substantial portions of stable irradiance in this range. Considering that the tropical test conditions should also be compatible with convenient outdoor measurements, stable irradiance conditions are necessary. Thus, 800 W/m2 is chosen for the irradiance intensity. To define the spectrum and the module temperature part of the tropical test conditions, the range of 700 to 900 W/m2 is considered as initial input parameters. [17]

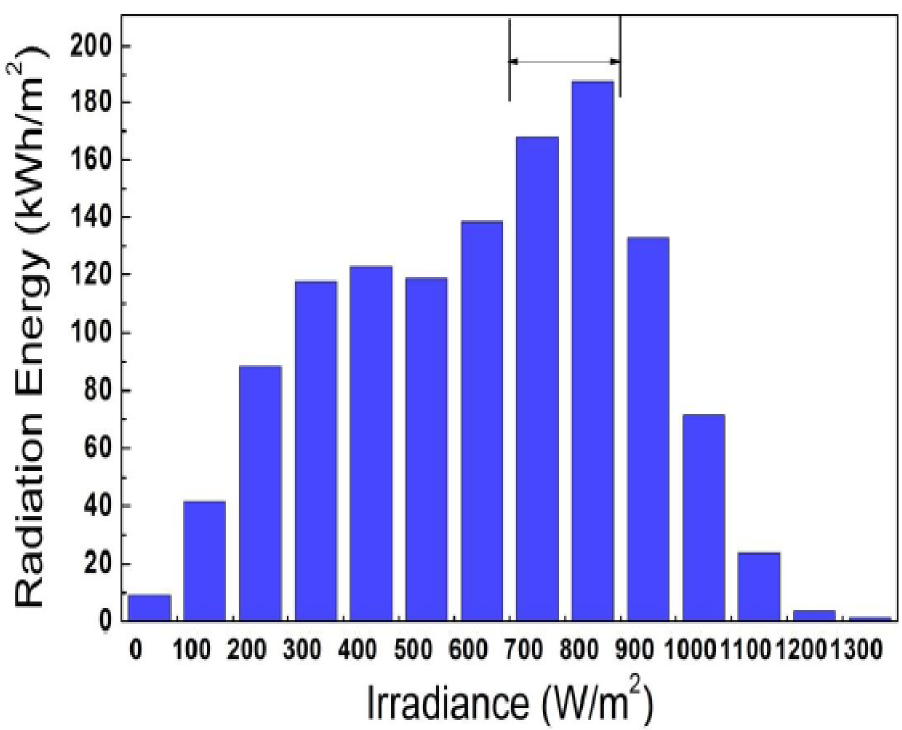

Fig.(6) Distribution of radiation energy with respect to irradiance level over year 2015.

Figure (7) shows the distribution of the solar radiation against the average photon energy, calculated for the range of (305 - 1150 nm) for all irradiance levels over the 1-year period of 2015. The radiation energy peaks at the average photon energy of 1.87 eV, while the average photon energy value for the standard spectrum is 1.83 eV. [18]

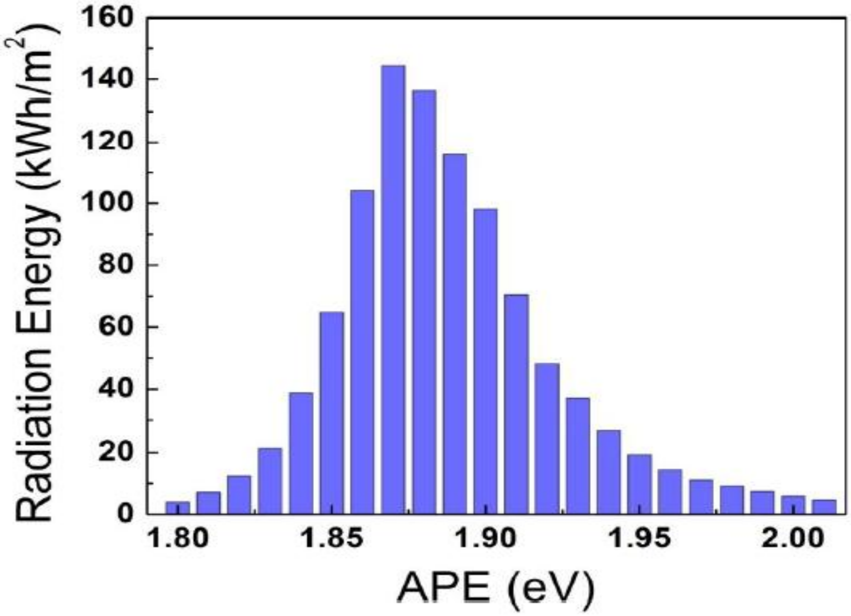

Fig.(7) Histogram of APE for all irradiance levels over the whole year of 2015.

For irradiances between 700 and 900 W/m2, the average photon energy is mainly around 1.88 eV, as shown in fig.(8) below.

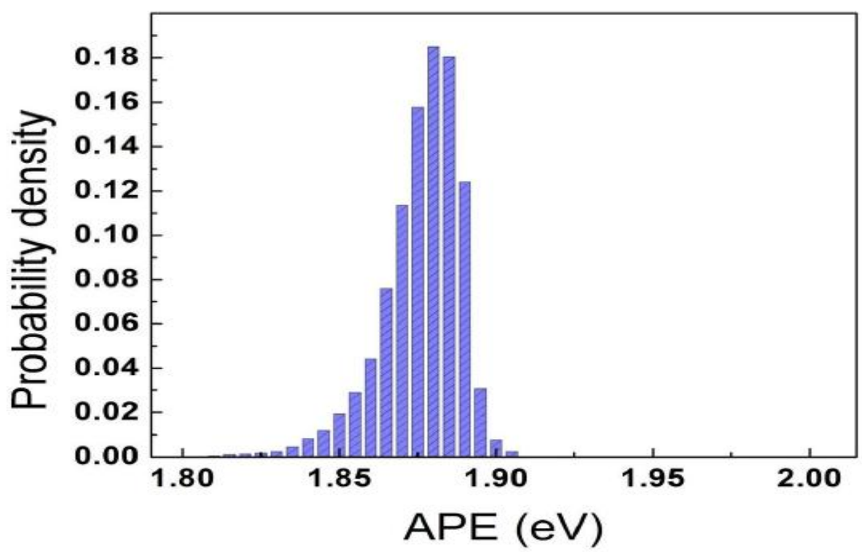

Fig.(8) Histogram of average energy with irradiance within the 700 - 900 W/m2 range.

The resulting annual average irradiance-weighted average photon energy is 1.879 eV. Thus 1.88 eV is chosen for the tropical test conditions. The spectral distribution was obtained by averaging the spectra with 1.880 ± 0.005 eV and irradiance 700 - 900 W/m2 of every wavelength into a single spectrum.

The distribution of module temperatures for the monocrystalline Si standard construction (glass/cell/ backsheet with aluminum frame) for all relevant irradiance levels is shown in Fig.(9). The other investigated PV module technologies show a similar distribution and hence are not shown additionally. To define a representative module temperature for the tropical test conditions, Figure (9) zooms into the irradiance range of 700 - 900 W/m2. [19]

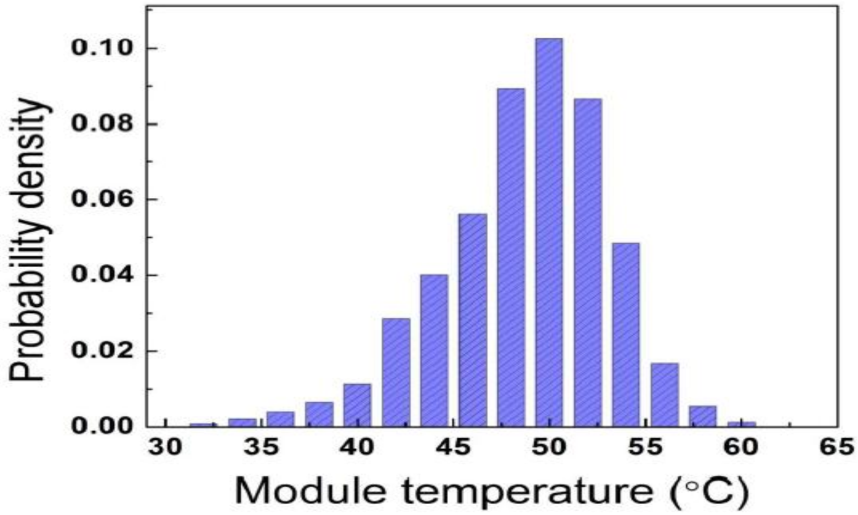

Fig.(9) Histogram of module temperature over a one-year period from 01-Jan-2015 to 31-Dec-2015, with irradiances between 700 and 900 W/m2. [20]

The resulting annual average irradiance-weighted module temperature is 49.5°C Hence we define the Tropical Test Conditions module temperature as 50°C. Data from 01-Jan-2015 till 31-Dec-2015 were used for this study. Results are shown in Figure (10).below. [21]

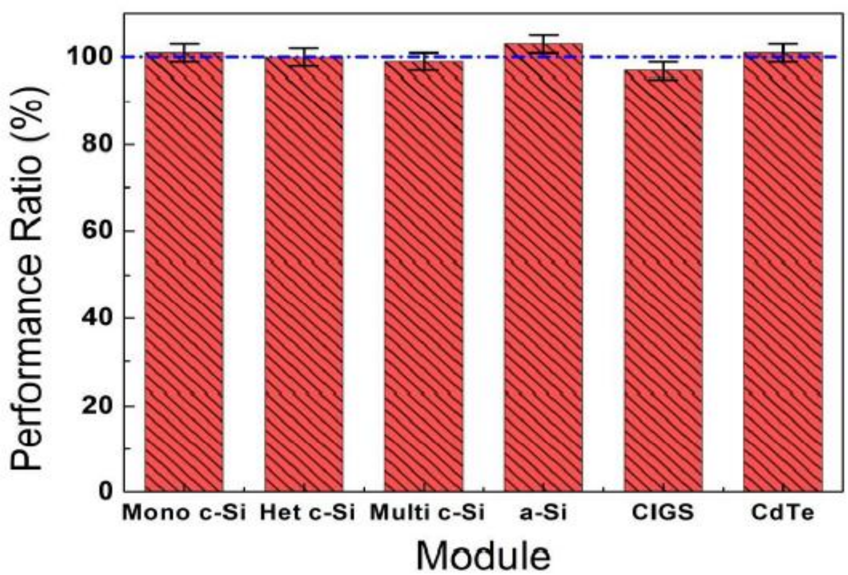

Fig.(10) Performance ratio based on newly defined Tropical Test Conditions , as proposed in this work. [25]

The biggest difference in performance ratio can be up to 18% (between single-junction a-Si and CIGS). Thus this value cannot provide reference information on whether the installation is good or not. In contrast, the performance ratio calculated based on the tropical operating conditions power (Figure 10) is close to 100% for all the modules studied, indicating that the overall outdoor operating conditions are close to tropical operating conditions. [24]

3.2 String Performance Measurements:

For each module the string voltages and currents are drawn as shown below. During the first day, August 26th 2015, two different strings were tested: 6-panels string and a 17-panels string. However, the first measurements of the 17-panels string presented problems continuously due to the heating of junctions. Thus, during the second day, on September 6th 2015, just a 6-panels string is measured. The stored electrical and climatic data are matched to analyze the measurements and to compare them with the theoretical results. [26]

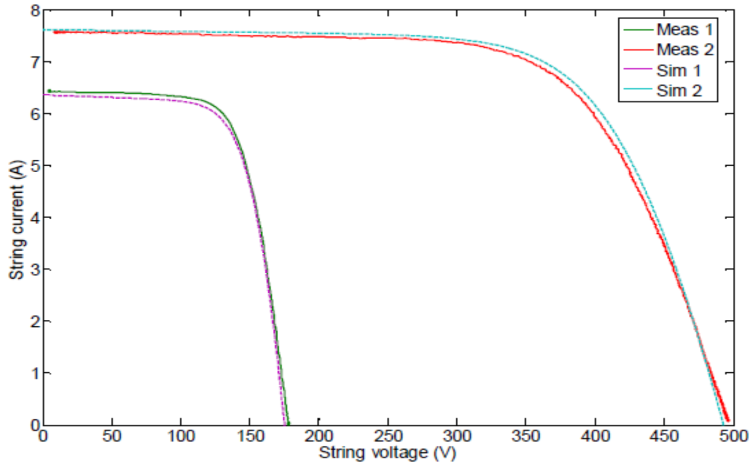

Fig.(11) Measured and simulated IV curves of the 6 modules string and the 17 modules sting from 26th August 2015.

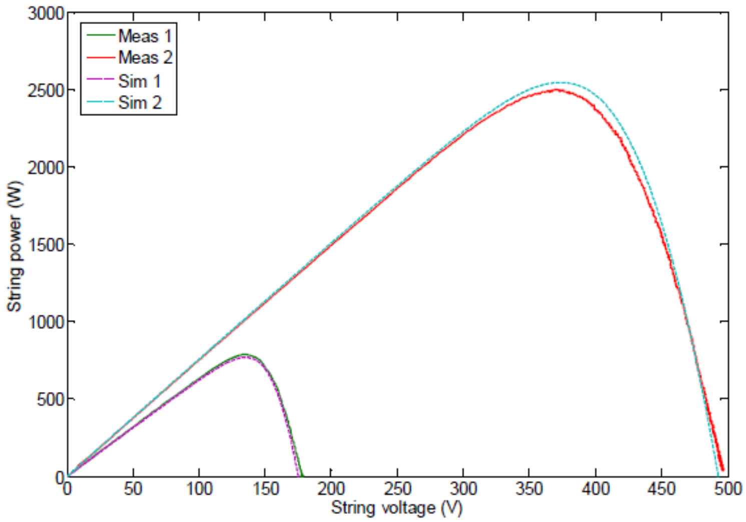

Fig.(12) Measured and Simulated PV curves of 6 modules string and 17 modules string from 26th August 2015. [26]

The simulated curves corresponding to the measurements show a appropriate reasonable behavior of the thermal module and PV generator modules. The differences between the simulated and experimental curves are relatively small, being the greatest for maximum power.

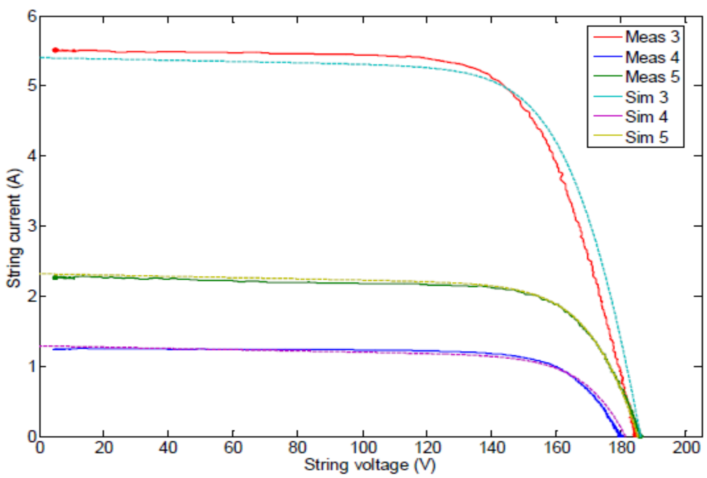

Fig.(13) Measured and Simulated IV curves of 6 modules string from September 6th 2015.

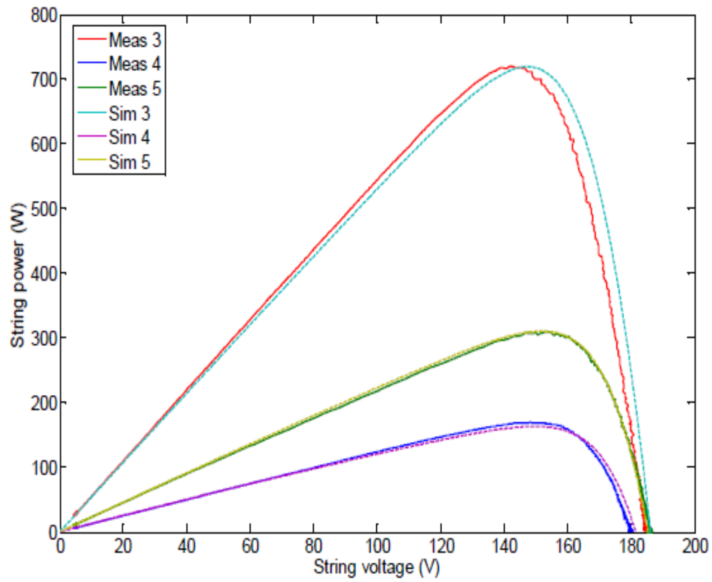

Fig.(14)Measured and Simulated PV curves of 6 modules string from September 6th 2015.

I-V and P-V curves of measurements show better the performance of a PV string under different operating conditions. Measurements were taken during a partially cloud day, hence the irradiance is the most significant parameter to compare the results. [26]

CONCLUSIONS:

Photovoltaic modules (panels) have potentiality of generating clean, silent, electricity without burning of fuel fossil which may cause tremendous damage to our natural environment. When photovoltaic is integrated in building envelope, it would serve a dual purposes, first generate electricity secondly serves as a building element. For the photovoltaic integration to fulfill its optimum goal it should uplift building appearance, and enhance aesthetic quality and flexibility of the building. The objective of this research is to investigate the efficiency of photovoltaic integration in building in hot and cold climates, and how could it be optimized for sustainable development. The methodology adapted was based on comparative case studies of office buildings from hot climate, where Iraq was chosen as case study area, and for cold climates. It was discovered that thin film PV panel is more appropriate for hot climates and polycrystalline for cold climates.

As it has been stated previously, in order for PV panels to operate efficiently, it is important to know latitude and optimum tilt angle of the area or region. It is important to know that solar radiations intensity is higher near equator and it decreases as we distance away. To obtain optimum tilt angle in hot and cold climate, in summer the optimum angle must be reduced by -15 degrees, in winter by +15 degrees. However in summer PV panels received solar radiation at higher angle and at lower angle in winter.

Thin film solar panel could be used both in hot and cold climates , it is however relatively very cheap compared to the other two, but its disadvantage is that it is less efficient than the other two types, therefore to compensate this set back, the installed area should be increased. For hot climate Thin film is the most appropriate type because it is more tolerant to heat, cheap and can operates even when the climate is cloudy and dusty, therefore in Iraqi telecommunication tower it is been used, due to the fact that the weather is semi desert, very hot, dusty in summer, therefore, thin film is highly recommended in hot climates. However poly-crystalline too can be used, because is less affected by high temperature, if we provide (15-20) gap or good ventilation or cooling using water for back of the cell it will operates efficiently, however it is more economically wise than mono-crystalline.

In cold climate the most recommended type of PV panel according to the literature is poly-crystalline, because it is efficiency is high in cold climate and more economically wise and it has longer life span. But it must be noted that all the three types can effectively operates in cold climate, but if we considered both efficiency, economical and payback time poly crystalline is the best. But all types can be jointly used in different ways in cold climate.

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