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A comparative Analysis of the Performance of Monocrystalline and Multiycrystalline PV Cells in Semi Arid Climate Conditions: the Case of Jordan

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Abstract

The energy consumption in the world is increasing greatly owing to the growing population, and to increasing energy consumption per capita. This high energy consumption is associated with a high life quality. Due to this fact, and to the energy price and availability and to the potential threat of global climate changes, there is a great motivation to use energy from renewable sources such as solar energy. Jordan is a developing non-oil production country and its energy needs are imported from abroad as oil and petroleum products. On the other hand, Jordan has an abundance amount of solar radiation 300 days a year. Photovoltaic modules provides safe, reliable, maintenance-free, without noise, and environmentally friendly source of power. This paper evaluates the performance of different solar modules in semi arid climate as in Jordanian. An experiment to investigate the performance of two photovoltaic modules is conducted at different times of the year. The measured parameters in this paper are: output open circuit voltage and short circuit current from the PV modules, ambient temperature and solar intensity. The relationship between the performance and the efficiency of monos crystalline PV and multi crystalline PV is measured in this experiment. The performance value of the PV solar module is identified and compared with the output values supplied by the producer of the PV modules and with other PV models.

Keywords: Renewable Energy, PV cells, PV Performance; PV Modules; PV in Jordan.

1. Introduction

There are several factors that form present interest in utilizing solar energy in the production of electricity. An earlier cause of this interest was the need to reduce dependency on imported oil of countries such as Jordan and to secure long term requirement of energy needs. Interest in renewable energy sources has been increasing rapidly as energy prices increased particularly after the Gulf wars in the 1990s.

Additionally, industrial practices and consumption patterns of the developed world seriously damage the environment and stimulated a search for clean and renewable energy sources.

As many countries concerned with increased levels of air pollution and climate change, Jordan is concerned with the reduction of CO_2 emissions to atmosphere. Data indicates that CO_2 emission in Jordan is below the world average value of 3.1 tons/capita/year [1].

In addition to other renewable energy sources, photovoltaic cells (PV) present a prime source of clean energy that utilizes energy from sunlight. Solar energy is converted directly to power without intermediate production of heat. Solar cells are used to heat water and PV cells to produce electricity. Photovoltaic cells are manufactured from fine films or wafers made from silicon [2,3]. They are semiconductor devices capable of converting incident solar light to DC current. Efficiency of produced power vary from 3% to 17%, depending on different causes such as the kind of technology used, the light spectrum, ambient temperature, system design, semiconductor characteristics and material of solar cell [4, 5]. The series or parallel connection of cells allows the design of solar panels with high currents and voltages (reaching up to 1 kilovolt). Solar panels are slow in degradation if they are sealed properly, which make them durable particularly as they have no movable parts and requires little maintenance. Different modules produce

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different amount of electricity according to required amount ranging from few watts to megawatts [3].

Photovoltaic energy conversion in solar cells consists of two essential steps. First, absorption of light generates an electron-hole pair. The electron and hole are then separated by the structure of the device; electrons go to the negative terminal and holes to the positive terminal, in effect generating electrical power.

At present, almost 95% of available solar cells are made of silicon. The advantage of using silicon is its mature processing technology, the large abundance in the crust of the earth, and non-toxicity that is imperative for the environmental. The silicon is used in PV cells for monocrystalline (single crystalline) and multiycrystalline wafer production and the production of thin film silicon modules. More than 90% of produced solar cell every year is based on crystalline silicon wafers. Thus, silicon-wafer based technology is important for the production of PV cells at present time [6].

The development of Si-PV technology materials is driven by cost reduction. The large growth in the PV market and need for lower cost material than monocrystalline make multicrystalline silicon a favorable alternative [7].

In general, performance of monocrystalline- silicon wafer is more expensive but better in performance than the multiycrystalline-silicon wafers. In single crystal silicon, the crystal lattice of the entire sample is continuous and unbroken with no grain boundaries. Multiycrystalline are composed of a number of smaller crystals or multiple small silicon crystals. Polycrystalline cells can be recognized by a visible grain (metal flake effect) and are more sensitive to thermal processing. Multicrystalline silicon wafers are usually characterized by their different grain sizes, orientations and higher content of defects and impurities [7].

Conversion efficiencies of commercial types of multiycrystalline –silicon cells are in range of 12–15% and could reach 17% using more sophisticated solar cell designs [8, 9]. In fact, the performance and the efficiency of multicrystalline solar cells is mainly limited by minority carrier recombination. Depending on the crystallization process, materials develop different defect structure, which determine and limit their efficiency. In general dislocations and **intragrain** defects such as certain impurities, small clusters of atoms or precipitates are mainly responsible for the recombination processes. Particularly localized regions of high dislocation densities are known to be rather detrimental [10]. Grain boundaries are less important because of the relatively large grains in the centimeter range. In order to improve multicrystalline cell efficiency, reduction of thermal load is required and implementation of guttering steps [11].

Multicrystalline silicon is either grown by an ingot or ribbon technique. The microstructures of multicrystalline silicon materials differ considerably depending on whether the material is grown by an ingot or a sheet growth technique [2,3]. Dislocations in ingot silicon are formed during crystal growth by plastic deformation to reduce the thermal stresses. Some of these dislocation networks show high recombination rates and are thus very detrimental to the lifetime of minority charge carriers. Therefore, improvement of multicrystalline silicon can be achieved both by the reduction of the dislocation density and the elimination of the bad regions where dislocations cannot be made passive [11].

Moreover, to modify the performance of multicrystalline silicon wafers, it is necessary to minimize the level of transition metals in the raw silicon material. To achieve low enough impurity levels, it is important to use the route via an easily cleanable silicon compound such as trichlorosilane (TCS) or monosilane.

2. Jordan Strategy for Solar Energy

During the last two decades, the increasing energy cost has posed difficult challenges for Jordan due to country's limited economic resources. To address these challenges Jordan has established a strategic transformation and restructuring of its national economy and energy strategy. The energy strategy aims to increase private sector participation in generation and distribution of electricity, promote competition and to establish an independent regulatory body for the power sector [14]. In accordance to this strategy, Jordan has assisted programs promoting solar energy. Assessment involved systematic monitoring of implementation of appropriate technologies, demonstrations and pilot projects [15–21].

A rural PV electrification program initiated by Quality-of-life improvement for the users—was launched in Jordan in 2002. An important element of this program is access to essential electricity of low-income and rural users [22]. Yet, the percentage of solar energy to total energy consumption in Jordan in 2002 - 2007 was estimated to be as low as 1.7–2.1% [23].

The potential of utilizing photovoltaic (PV) technology in Jordan is substantial as many remote and isolated locations are far from the national electrical grid and are not expected to be connected in near future. In 2002, the Jordanian Government launched a project aimed at utilization of PV generators in rural sites. A solar hybrid power facility to produce 100-150MW was constructed in Quwairah, south of the country. Jordan is aiming to add 300MW of Concentrating Solar Power (CSP) by the year 2020 [14].

Decreasing cost of PV cells and market trends raise motivation towards developing PV systems. For example, between 1976 and 2008, the capital cost of PV modules per watt of power capacity in Jordan has declined from about $58 per watt to less than $4 per watts [24].

This paper evaluates the performance of two solar modules. Experimental data was collected in three locations in Amman city in Jordan. The performance was investigated at different times in the day and different months. Ambient temperature and solar radiation was registered.

3. Existing Knowledge

3.1. PV Modules

Solar cells are assembled into modules or module connected to charged battery, available modules are designed to deliver direct current (DC) at slightly over 12 Volts (V). A typical crystalline silicon module consists of a series circuit of 36 cells, encapsulated in a glass and plastic package for protection from the environment. This package is framed and provided with an electrical connection enclosure, or junction box. Typical conversion efficiencies (solar energy to electrical energy) for common crystal line silicon modules are in the range 11 to 15% [3].

There are four advanced thin film technologies, their names are derived from the active cell materials: cadmium telluride (CdTe), copper indium diselenide (CIS), amorphous silicon (a-Si) and thin film silicon (thin film-Si). Amorphous silicon is in commercial production while the other three technologies are slowly reaching the market. Thin film modules are made directly on the substrate, without the need for the intermediate solar cell fabrication step. Some manufacturers are developing PV modules that concentrate sunlight onto small area high efficiency PV cells using lenses. The concept here is that the lens material will be less expensive per unit area than conventional silicon modules thus resulting in a $/Wp advantage. To ensure that the concentrating lenses are always focused on the PV cells, these modules must always be directed at the sun and therefore must be used in conjunction with sun trackers. These modules are limited to areas which has a considerable amount of direct beam sunlight, as in desert regions [5].

3.2. PV Applications

Photovoltaic can be classified based on the end-use application of the technology. The most common PV projects are off-grid applications. Water pumping also represents an important application of PV, particularly in developing countries. The largest long term market potential for PV, in volume of sales, is with on-grid applications.

On-grid applications

In grid connected applications, also called “On-grid” applications, the PV system feeds electrical energy directly into the electric utility grid (this includes central grids and isolated grids). Two application types can be distinguished, distributed and central power plant generation . An example of a distributed grid-connected application is building integrated PV for individual residences or commercial buildings. The system size for residences is typically in the 2 to 4 kWp range. For commercial buildings, the system size can range up to 100 kWp or more. Batteries are not necessary when the system is grid-connected. Another application is the installation of “PV generators” by utilities at power substations and “end-of-line” sites. These applications can be on the threshold of cost competitiveness for PV, depending on location. For example, the Sacramento Municipal Utility District (SMUD) in California has been implementing a plan to install more than 1 MWp per year of distributed PV in its service area [4].

Benefits of grid-connected PV power generation are generally evaluated based on its potential to reduce costs for energy production and generator capacity, as well as its environmental benefits. For distributed generation, the electric generators (PV or other) are located at or near the site of electrical consumption. This helps reduce both energy (kWh) and capacity (kW) losses in the utility distribution network. In addition, the utility can avoid or delay upgrades to the transmission and distribution network where the average daily output of the PV system corresponds with the utility’s peak demand period (e.g afternoon peak demand during summer months due to air conditioning loads), as described in Leng and Martin (1994) . PV manufacturers are also developing PV modules which can be incorporated into buildings as standard building components such as roofing tiles and curtain walls. This helps reduce the relative cost of the PV power system in buildings.

Off-grid applications

Using PV is most competitive in distant sites from electric grid and relatively requiring small amounts of power, less than 10kWp. In off-grid applications, PV panels are used to charge batteries, storing the produced electricity the modules and providing users with electrical energy as demand.

Competition in the use of PV in remote off-grid power applications is with grid extension; disposable batteries; fossil fuel and thermoelectric generators. The cost of grid extension in the US, estimated by the Utility Photovoltaic Group (UPVG) ranges from $20,000 to $80,000 per mile. Thus, PV competes well against grid extension for small loads, far from the utility grid. Compared to fossil fuel generators and primary batteries, key advantage of PV is reduction in operation, maintenance and replacement costs; these often result in lower lifecycle costs for PV system. Off-grid application includes both stand-alone and hybrid systems, which are similar to stand-alone systems but also include a fossil fuel generator to meet some of the load requirements and provide higher reliability [4,5].

4. Experimental Setup and Devices

In order to carry out the performance test for different PV modules, the following experimental setup has been conducted in the experiment.

4.1. The photovoltaic System

Two different modules of PV panels arranged in a series–parallel connection are tested:

- a PV module has solar cells made of mono-crystalline silicon (Fig. 1, a).
- a PV module has solar cells made of multi-crystalline silicon (mc-silicon) (Fig. 1, b).

Figure 1 (a): Monocrystalline PV Cells

Figure 1 (b): Multiycrystalline PV Cells

Orientation and inclination angle of the solar panel significantly affect efficiency and output power. The two tested panels were installed on the same frame to inshore a similar inclination angle for both PV models. Best orientation for PV panels is to the south in Jordan to increase total energy incident on the collector surface during day light. The PV panels were placed to face south at 32º angle as Amman has a latitude of 31º57' north [25]. This angle can be reduced to less than altitude to maximize power in summer and to be larger than latitude in winter to maximize collected energy.

4.2. Battery Storage

PV systems require energy storage to store the generated electricity during day light to use when needed. Most used battery types are lead-calcium and lead-antimony. Nickel- cadmium batteries are also used particularly if battery is subjected to a range of temperatures. The changing nature of solar radiation requires batteries that can undergo charge and discharge cycles without damaging. The amount of battery capacity that can be discharged without damaging the battery depends on battery type. Lead calcium batteries are most suitable in “shallow cycle” applications where less than 20% discharge occurs in each cycle. Nickel-cadmium batteries and some lead-antimony batteries can be used in “deep cycle” applications where the depth of discharge may exceed 80%. Depending on site conditions and presence of a backup generator, battery banks are sized to provide a period of system autonomy ranging from a few days to a couple of weeks [e.g. 25].

Batteries are distinguished by their voltage, which for most applications is a recurrent of 12V. Battery capacity is expressed in Ampere-hours (Ah). For example, a 50 Ah, 48 V battery stores 50 × 48 = 2,400 Wh of electricity under nominal conditions. Optimization of battery size is important to extend battery life and optimal system performance and life-cycle costs. Unnecessary battery replacement is costly, particularly for remote applications.

4.3. Inverter

Inverters are power electronic devices used in various photovoltaic systems to convert direct current to a 50-Hz alternating current conforming to the grid.

The output power of tested photovoltaic panels in the present investigation was measured by calculating output current and voltage using an ohmmeter.

4.4. Pyranometer

A pyranometer is used to measure broadband solar irradiance on a plan surface and solar radiation flux density (W/m^2) of an angle view of 180º.

4.5. Speedometer

A speedometer is used to collect and record air velocity, temperature, humidity and wet bulb.

5. Experimental Approach

The experimental investigation has been carried out at the venue of the University of Jordan in Amman, Jordan. Experiment measurements started from January to the end of May. Measurements were taken from the two PV modules in three days of each month. Taken readings included the following:

- Open circuit voltage and short circuit current readings produced at the output of the PV cell. Solar radiation, ambient temperature, humidity and wetness, wind speed. Keeping similar conditions for the two tested PV panels.
- Efficiency of each panel under the recorded conditions was calculated. Input power has been calculated by multiplying the incident solar radiation with the PV area. Output power has been calculated using measured values of the generated voltage and current. Efficiency variation accordance to solar radiation and output conditions has been calculated and presented in the next section.
- Computer software has been used to specify cash flow diagram and to calculate payback period of the PV system.

Figure 2 shows the schematic diagram of PV panel system with all components such as charge controller, inverter, batteries and DC and AC load. The devices that have been used in the experimental work and their specifications are presented in Table 1.

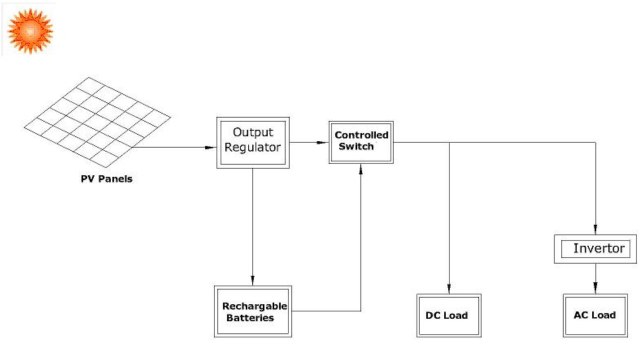


Figure 2: Schematic diagram for the PV system

Table 1: Specifications of devices used in this experiment

Devices	Manufacturer	Model	Specifications
PV Solar Panels Type 1	KYO CERA Corporation	KC 70	Max. power 75w outputs power 70v circuit volt 2105v output volt 16.9v Current 4.14 A
PV Solar Type 2 multi	TUV Rheinland	BP 585F	Nominal peak power Pm = 85. w Peak power voltage 18.v Power peak current 4.72 Short e.c I_{sc}=5A opent c. Volt V oc= 22.03v
Pyranometer +	Solar light co. inc. +	PMA 2144	Min. power Pmin=80w
Integrator	KIP and Zonen B.V	01127	Sensitivity = 15.42± 0.24 µV/W/m^2.
Voltmeter	UNI -T	DT 830	

6. Experimental Results

Solar radiation on a horizontal surface in Amman city varies from one month to another. There's also a wide variation in total daily radiation on horizontal surface in a same month, caused by the inclination angle of solar radiation and weather conditions.

Radiation intensity has high level in sunny days, and decreases to an insufficient level in cloudy weather. Variation in solar radiation is also caused by earth's rotation around its axis. At early morning solar radiation has a low angle and solar rays penetrate a thick atmospheric layer. Abundance in radiation occurs at noon, when sun is at the highest angle above the horizon and radiation encounters minimum thickness of the atmosphere. Solar radiation also differs according to seasons, in winter the sun becomes lower in the sky and higher in summer because sun ray's angle changes due to the earths tilt angle [25].

Figure 3(a-e) shows the measured ambient temperature as a function of time for several days in each month from January to May. Ambient temperature was measured at different times during test days starting 8:00am to 4pm. Fig. 3 indicates that temperature varies significantly during the day and in most cases from one day to another of the same month. For example, Fig. 3(a) shows that in January at 8am, measured temperature was 9°C and rises to about 17°C at midday and decrease to 14°C at 4pm. Yet, the measured temperature is higher than the measured temperature in the morning. This temperature behavior is noted in the months January to May. Such rapid climate change in the same season produces a noted gap in temperature readings which affects the efficiency performance, as shown in the efficiency curve below Figure 3.

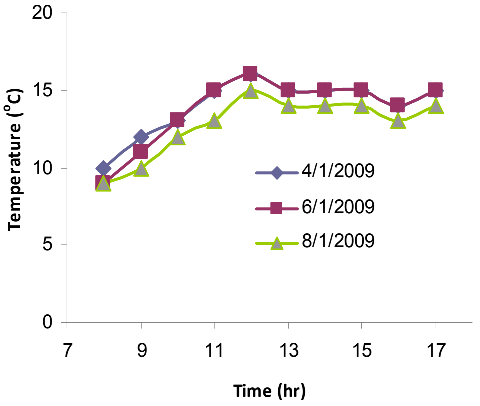


Figure 3 (a) January 2009

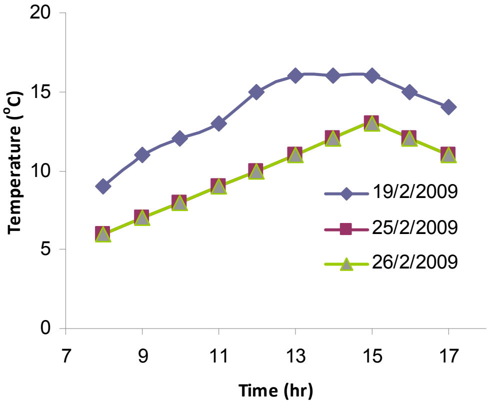


Figure 3 (b) February 2009

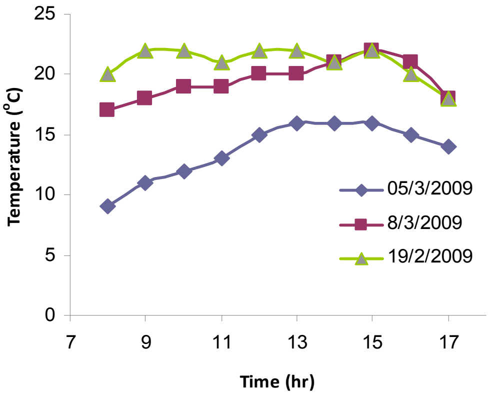


Figure 3 (c) March 2009

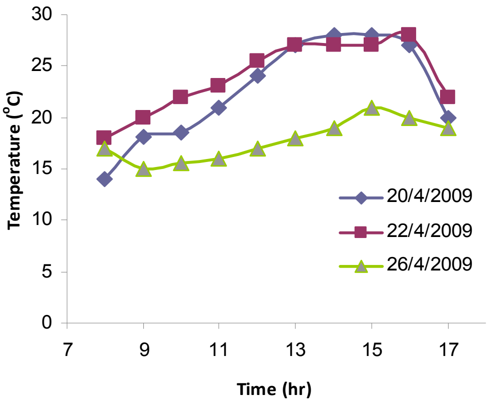


Figure 3 (d) April 2009

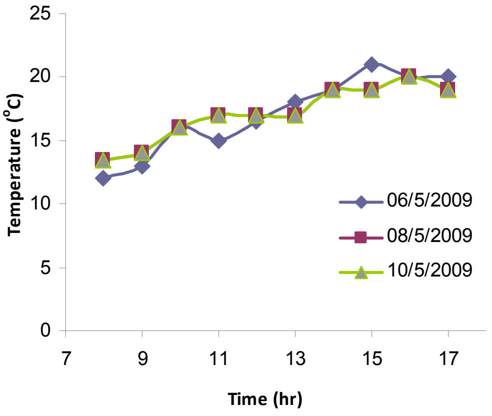


Figure 3 (e) May 2009

Figure 3 (a-e): Ambient temperature measurement as a function of time for different days in the months January to May

Variation in ambient temperature during the day affects received radiation intensity accordingly. The highest radiation intensity was obtained at mid day when sun ray is perpendicular on the surface. The recorded values are in the range 600 W/m^2 in the morning and afternoon and 1100W/m^2 at midday. The variation in radiation intensity caused variation in the measured output current which affects efficiency in the same manner. Fig. 4 shows solar radiation measurement per hour in randomly selected three days in the months January to May. January to March represent winter season in Jordan, April and May spring. Figure 4 shows radiation intensity is a little lower during the days in winter than those in spring particularly in the morning. However, it can be concluded from Figure 4 below that solar radiation in winter is enough to utilize PV system in Jordan.

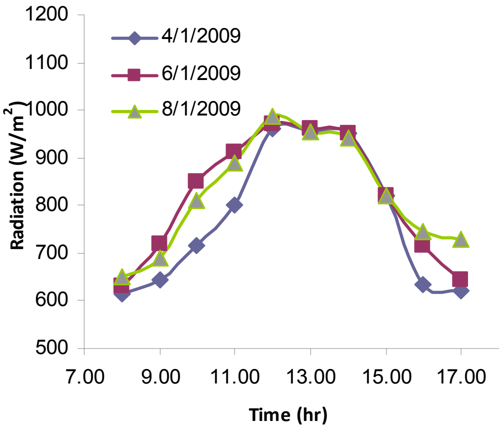


Figure 4 (a) January 2009

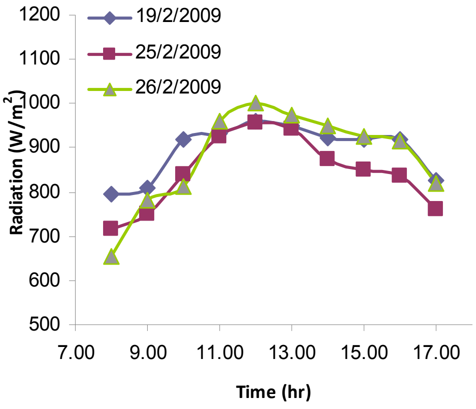


Figure 4 (b) February 2009

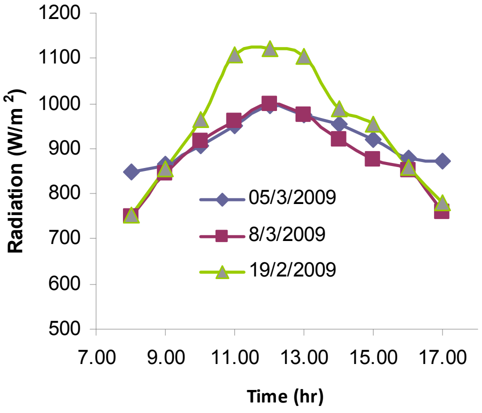


Figure 4 (c) March 2009

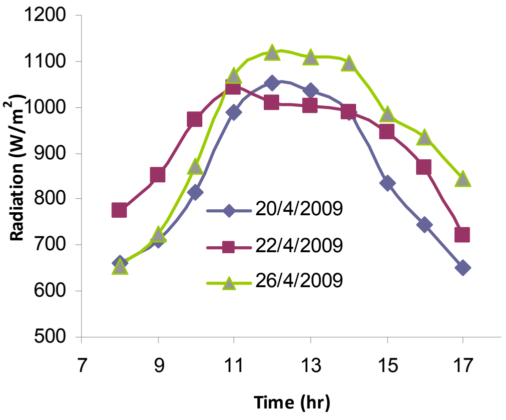


Figure 4 (d) April 2009

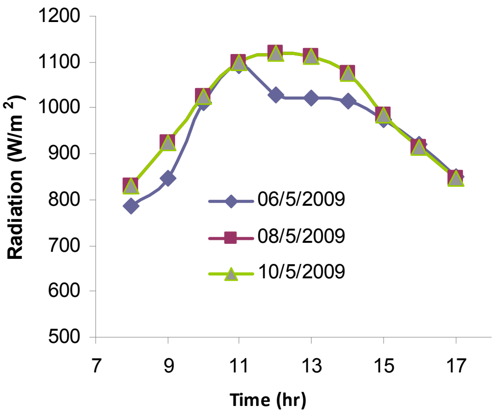


Figure 4 (e) May 2009

Figure 4 (a-e): Measured solar radiation as a function of time for different days each month

Output current and voltage of each panel was measured every hour in a randomly selected day each month under similar conditions. The open circuit voltage and short circuit current has been measured directly from the PV panels output without battery connection or electrical load. The efficiency curve of mono crystalline and multi crystalline PV panels is plotted.

Figure 5(a-e) shows the comparison of the produced current of mono crystalline and multi crystalline PV panels of each month. The output current of mono crystalline is higher than that of the multi crystalline PV panel at all times in days and months.

Finally, factors that affect the electrical characteristics of the PV solar panels are summarized as:

- The amount of sun rays reaching the cells
- number of cells in the panel
- types of silicon PV solar cells
- temperature of the PV solar panels
- area of each PV panel
- system losses effect such as losses due to cables and blocking diodes
- charge status of battery.

In the present experimental investigations, the batteries did not used in the measurements. Also, the inverter which changes the DC output battery to AC voltage of the load was not used in this experiment. Therefore, the effect of the inverter and batteries on the system efficiency has been not discussed in this work.

However, the ambient temperature has a considerable effect on the efficiency of PV system. As the ambient temperature increases cell temperature increases, the open circuit voltage decreases and the short circuit current become slightly higher to reach the maximum output current. In the present investigations, the measurements for both types of PV panels have been carried out at the same time which means that the ambient temperature and temperature of the PV panels were identical. Therefore, the influence of ambient temperature on the efficiency of PV panels is abandon.

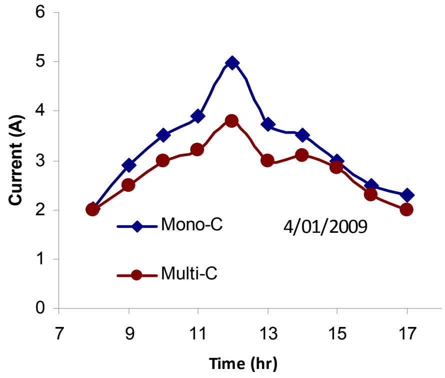


Figure 5 (a) January 2009

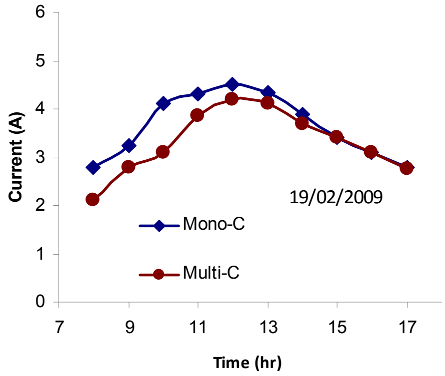
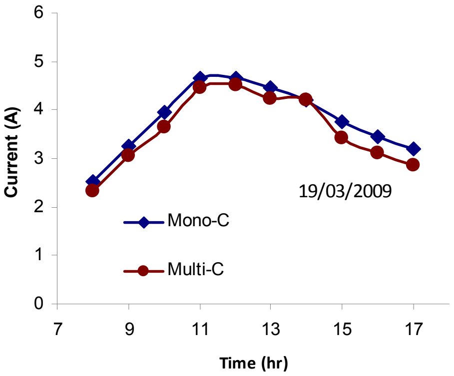


Figure 5 (b) February 2009



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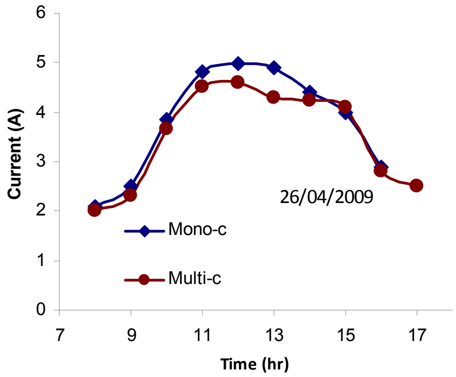

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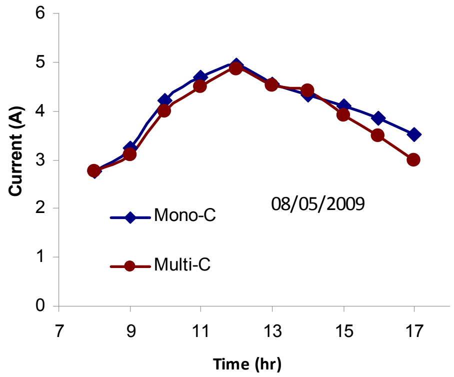


Figure 5 (e) May 2009

Figure 5 (a-e): Output current measurement of mono-crystalline & and multi crystalline PV panels as a function of time of one day in each month

Figure 6 (a-e) illustrates the efficiency curves for both mono crystalline and multi crystalline PV cells. Figure 6 indicates that mono crystalline PV cells have higher efficiency value than multi crystalline PV cells. The efficiency of mono crystalline PV cells can reach 18% while efficiency of multi -crystalline PV cells reaches 16%. Thus, output power of mono crystalline is higher than that of multi crystalline PV cells. Efficiency curves display constant values owing to weather change during the day. Efficiency increases rapidly with solar irradiance. A maximum peak occurs at midday when radiation intensity reaches maximum.

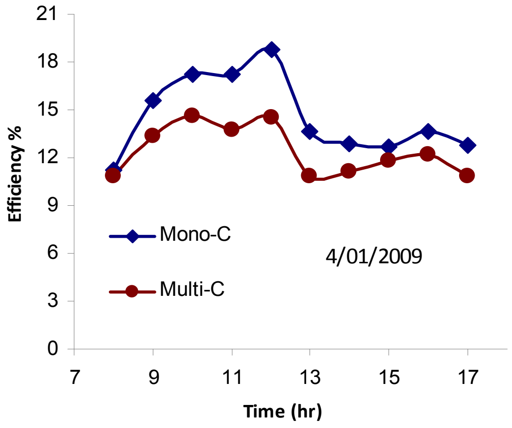


Figure 6 (a) January 2009

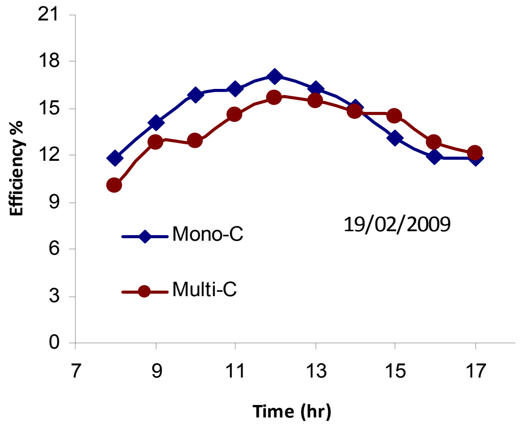
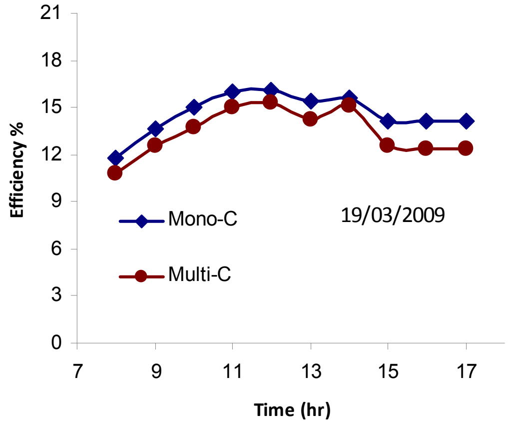


Figure 6 (b) February 2009



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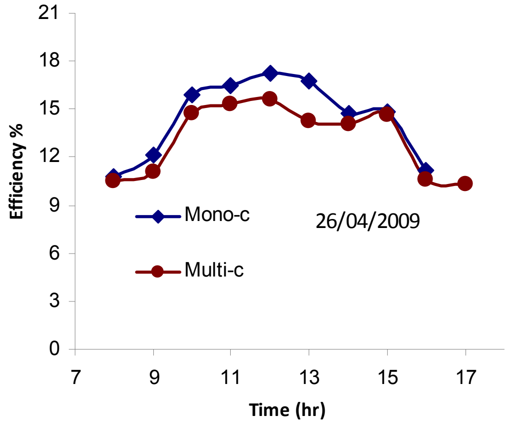

Figure 6 (d) April 2009

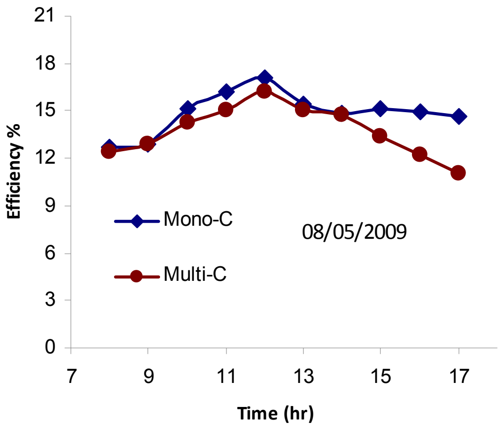

Figure 6 (e) May 2009

Figure 6 (a-e): efficiency behaviors of mono-crystalline &-multi crystalline PV panels as a function of time of the selected days in each month

Figures 5a and 6a show output current and efficiency of the two PV modules in January, both indicate graduate increase in irradiance. The PV solar modules show the peak values for the output current and efficiency at noon time. Cloudy sky on the 4th of January caused efficiency reduction and the generated power from 2:00pm onward. Figure 5b and 6b shows similar results for February. It is found that maximum values of output current and efficiency occur at noon time. The same trend is noted in March, April and May.

7. Conclusion and Recommendations

A performance test of mono-crystalline and multi-crystalline PV panels has been carried out in this paper. This test was conducted in **semi arid climate conditions** in Jordan. Short circuit current and open circuit voltage data were recorded of the tested PV panels. Input power has been calculated based on measured solar radiation. Output power of the panels is calculated from the measured values of generated current and voltage. Efficiency of mono-crystalline and-multi crystalline PV panels was measured in different days of each month. Findings indicate that efficiency of mono-crystalline is higher than that of the multi-crystalline PV panels.

Factors found to be taken into consideration while comparing the two PV types include:

1. Wear of utilized cells as the efficiency is reduced with a longer life-time period.
2. Cell type affects its performance in which the semi-silicon is classified as the best.
3. weather conditions, readings in rainy days are excluded because of absence of adequate radiation.

The comparison of the efficiency of the multi-crystalline and mono-crystalline PV panels indicates that despite similar behavior of both PV modules in the selected days and months, mono-crystalline panel efficiency was higher than that of the multi-crystalline panel. However, the difference between the efficiency of both models was relatively small.

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