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Performance Study of On-Grid Thin-Film Photovoltaic Solar Station as a Pilot Project for Architectural Use

Bashar K. Hammad[*,a], Shaher M. Rababeh[b], Mohammad A. Al-Abed[c] and Ahmed M. Al-Ghandoor[d]

[a] Mechatronics Engineering Department, the Hashemite University, Zarqa, Jordan

[b] Architecture Engineering Department, the Hashemite University, Zarqa, Jorda

[c] Biomedical Engineering Department, the Hashemite University, Zarqa, Jordan

[d] Industrial Engineering Department, the Hashemite University, Zarqa, Jordan

Abstract:

We present a full description of a pilot photovoltaic station with thin-film modules, a newly-introduced technology in the market of solar systems in Jordan. In order to take the issue of landscaping of outdoor spaces in a hot semi-arid environment, give the Hashemite University campus a unique identity, and improve its aesthetic image, this pilot station has been installed as a canopy covering for 4-car parking space. The system is tested for a two-month period to check its behavior in the Northeastern sector of Jordan environmental conditions and study the effect of local climate. The system is connected to the local grid via a solar inverter. Measurement and monitoring systems are utilized to acquire data necessary to analyze the system performance. We investigate the effect of the system location, modules and ambient temperatures, wind, and dust on the system efficiency. We show instantaneous and daily average data for several performance metrics. The preliminary results show that the efficiency of the system is within the normal range for this type of technology tested in other countries. Harsh environment of Jordan semi-arid region has adverse effects, where the efficiency of the system is reduced by about 10% due to accumulation of dust. However, a feasibility study is planned in the near future after obtaining sufficient data to evaluate the economic value of thin-film systems in Jordan.

Keywords: Pilot Study; Thin-film;On-grid; Efficiency; Semi-arid environment; Dust;Landscape;Visual Impact.

1. Introduction

Two factors forced decision-makers in Jordan to think seriously of changing the reliance on traditional sources of energy into renewable sources; dependence on oil imported from outside and surge in its price. Solar energy, as one of the most important sources of renewable energy, obtains increasing attention in Jordan. Jordan is considered one of the sun-belt countries where the average annual solar radiation per day is 3.8 kWh/m2 in winter and more than 8 kWh/m2 in summer. In addition, the average sunshine duration is more than 300 days per year, and the yearly global solar radiation ranges from 1700 kWh/m2 in Jordan valley and over 2250 kWh/m2 for hill area [1].

It is important to mention that to the best of the authors' knowledge, all these PV systems, installed in Jordan for residential or commercial use, are of mono- or polycrystalline modules; there is no published data on the efficiency and functionality of thin-film PV system in semi-arid environment in Jordan. Although thin-film technologies were developed to reduce the cost of solar cells significantly [2; 3], the relatively low efficiency, compared to "traditional" PV technologies, makes it unattractive for consumers.

Razykov et al. [2] reviewed the progress made of mono- and poly-crystalline and thin-film photovoltaic manufacturing based on Si, semi-conductor and nano-technologies. They reported the efficiency of modules from several manufacturers ranging between 1.7% and 12.0%. However, research results showed that efficiencies up to 19-20%, for CIGS (Copper Indium Gallium Selenide), and 40%, for multi-junction III-V materials, can be achieved. In [4], Muñoz-García et al. analyzed different thin-film technologies to find the easiest method for obtaining the current-voltage (I-V) characteristics at standard conditions.

Thin-film PV technology utilized in a wide range of application, Yoon et al. [5] integrated transparent thin-film amorphous modules on the front windows of a building in Korea. After monitoring the system for 2 years, they reported that an electrical power of 580.5 kWh/kWp/year was generated.

Dust, humidity, and air speed are among the environmental factors that affect efficiency of PV systems. However, the study of Mekhilef et al. [6] is one of few studies on the effect of these three factors all together at the same time on the performance of PV cells.

However, Campus Master Plan for the Hashemite University (HU), as one contemporary building project

* Corresponding author. e-mail: bkhammad@hu.edu.jo.

constructed in a semi-arid zone, did not take into consideration the landscape issue of the outdoor spaces. Ill-planning for the outdoor spaces is clear where no efforts have been made to apply any passive design concepts. Adapting to the hot and arid climate in the HU campus, users like to stay at outdoor places, such as courtyards, streets and other open spaces in the summer time. However, the design of the university master plan does not include a decrease in solar exposure to maximize the frequency of acceptable thermal conditions resulting in exacerbating the urban heat effect. By recognizing how well HU campus outdoor spaces respond to the needs of faculty, students, and staff, one can recommend ways of improving the outdoor environment necessary to facilitate the work and learning experiences of different users within the campus and the desired student-faculty interaction.

For this purpose, the decision has been made to construct 5 MWp PV plants at HU. The proposal is to divide them into two forms; 4 MWp as a farm station on a hillside in the university, and 1 MWp PV system as distributed shelters for pedestrians and canopies for car parks. The users as local community were involved in the decision for this project and committed to the future care of the landscape elements. Project enhancements may cover sidewalk improvements, furnishings, lighting, and car parks. New elements should be properly integrated with and linked to existing streetscape elements and should contribute to creating a sense of place and university identity. In order to address the issues mentioned above and as a first step to give HU campus a unique identity, and to improve its aesthetic image, a pilot station has been installed as a canopy covering for 4-car parking space, (Figure 1). We installed a PV system in a shade-free location at the south side of the workshops of the Faculty of Engineering at HU (Figure 2). However, addressing this novel idea and strategy at HU will identify the PV plants as one of the technologies that would contribute and create more comfortable outdoor spaces for the inhabitants and their belongings. A discussion on how this procedure may be used and integrated into the administrative requirements of large and small scale PV plants developments is carried out.

The issue of visual impact seems to be the greatest. The visual impact, due to its subjective nature, is one of the main barriers that the wide adoption of solar panels could face [7]. The critical elements of the visual and aesthetic impact from the solar energy systems are the integration of their characteristics in the design, and the rational sitting of the solar parks. The studies, concerning the procedures for assessing the territorial and landscape impacts of this type of systems, have recently seen a remarkable development [8; 9]. Landscape planning is setting the scale for a sustainable utilization. The main characteristics of a coherent landscape compose a state where all the functions and the processes are integral parts of the harmonious route in time and space. This coherence can break when building materials are used or when new structures are not related to the typical character of the region. Very often the integration can be solved by taking into account not only the visibility of the plant but also other aspects of the perception that are more difficult to measure, such as the shape and color of the artefacts. In this sense, the “clerestory concept” is implemented in the design of car-parking canopy, (Figure 1) for supplying natural light and circulation of fresh air.

The thin-film technology is selected in this pilot project where a large shaded area is required, because it has a larger surface area per kWp of power generated compared to poly- and mono-crystalline technologies. Thin-film modules have a surface area of 16 m2/kWp, whereas it is 7 m2/kWp for monocrystalline modules and 8 m2/kWp for polycrystalline modules [10].

Figure 1. Solar PV parking installed at HU.

Figure 2. Aerial view of PV system at HU

The remainder of this paper is organized as follows: Section 2 describes the PV system, while Section 3 explains the measurement and monitoring system implemented to acquire and analyze data. Section 4 discusses some of the most important results obtained thus far, before we conclude some final remarks in Section 5.

2. Design and Setup

The system is oriented towards the exact south and is fixed at 30º from the horizontal (optimal inclination for maximum annual energy yield in Jordan). The system has the following features:

- 20 thin-film modules of 150 W (+\-5%) at the standard test conditions (STC). Technical specifications of each module are shown in Table 1.
- The system is composed of two strings connected in parallel. Each string has two parallel arrays and each array has 5 modules connected in series. By

implementing this design, a maximum current of 9.28 A and 323.5 V at STC are obtained, which are well below the maximum inputs to the solar inverter (Table 2).

- A steel/Aluminum frame to support the system.
- A Solar inverter, which a device that inverts DC power generated from the PV system into AC power synchronized with electricity available in local grid. Technical specifications of the inverter supplied with this system are shown in Table 2.

Table 1. Technical specifications of thin-film PV modules at Standard Test Conditions (STCs)

Parameter	Value
Open circuit voltage (V)	85.5
Short circuit current (A)	2.54
Maximum power voltage (V)	64.7
Maximum power current (A)	2.32
Power reduction (%/ºC)	-0.28
Dimensions (mm)	1412×1112

Table 2. Technical specification of solar inverter

Parameter	Value
Maximum efficiency (%)	97.0
Maximum DC input power (W)	3200
Maximum DC input voltage (V)	550
Minimum DC input voltage (V)	125
Start Voltage(V)	150
Maximum input current (A)	17
Maximum AC apparent output power (VA)	3000
Maximum output current (A)	16
Power factor	1

3. Measurement Instruments And Data Logger

In this work, the system is equipped with the following sensors:

- Senor box: it is used to measure solar radiation and modules and ambient temperatures. It provides data logger (described later) with continuous meteorological data. It is installed next to the PV system at the same orientation to measure total radiation without any need for further calculations. The solar radiation sensor consists of a PV cell type (amorphous silicon - aSi) with a measurement range between 0 and 1,500 W/m² and accuracy ± 8 % with a resolution of 1 W/m². The modules temperature sensor is attached underneath one of the modules far from the direct sun light. The module temperature sensor consists of a PT100 resistance and operating range between −20 °C and +110 °C and accuracy ± 0.5 °C with resolution of 0.1 °C
- Ambient temperature sensor: it consists of a PT 100 resistance and is connected to the sensor box described above. It is installed in a plastic enclosure and in the shade underneath system far from the direct sun light. Its operating range is −30 ºC to +80 ºC with a tolerance of ± 0.7 ºC.
- Anemometer: it is installed at the top of system. It measures wind speed between 0.8 m/s to 40 m/s with 0.4 m resolution.
- A data logger is used for remote monitoring, diagnosis, and configuration of the PV system. It receives and stores simultaneously measured values and data from PV inverter and sensors. Data transmission takes place via the international wireless standard, Bluetooth, allowing remote inspection of the system at any time, detection of operational faults at early stages, and adjusting operating parameters from any location in the world as long as there is an internet connection. The data collected can be displayed daily, monthly, and yearly. It has a maximum communication range up to 100 m, an internal memory of 12.5 MB, and external memory (SD card) up to 2 GB.
- The shaded area (vertical projection), provided by the system as a whole, giving the system its architectural functionality as solar canopy, is about 10 m in length, and 5 m in depth, providing each car with about 12.5 m^2 of functional shade, that was not available for cars beforehand.

4. Results and Discussion

Sun path and ambient temperature vary from winter to summer and from day to day, and, consequently, affects the efficiency of PV modules. The Energy Efficiency is calculated simply as the output energy (electricity generated) divided by input energy (solar radiation). Mathematically, it is given by

$$\eta = \frac{\text{Output}}{\text{Input}}\% = \frac{\text{Power}}{\text{Direct Irrediance}}\% = \frac{\text{I}\cdot\text{V}\cdot\text{power factor}}{(\frac{\text{Irradiance}}{m^2})\cdot(\text{module area } (m^2))\cdot\text{number of modules}}\%$$

where I and V are AC current and voltage, respectively, recorded by data logger, and assuming a power factor (PF) of 1 as an output of the inverter.

We ran the experiment on July 20th, 2012 for 60 days. Data for Five days (Days 22, 26, 41, 52, and 54) is missing or corrupt due to main power blackout (system is designed to shut down when main power is cut for safety purposes). We set the data logger to acquire measurements every five minutes. Figures 3 and 4 show the current and voltage, respectively, recorded during the period of the experiment supplied to the local grid (AC power). The maximum current (approximately 11 A) is below the limit of maximum output current (check Table 2 for inverter specification). In Figure 3, values for instantaneous current go from zero at the beginning of the day until they reach a maximum when the total radiation reaches its maximum for the day, Figure 5. However, the instantaneous voltage in Figure 4 jumps suddenly from zero to higher values when the voltage reaches a certain threshold set by the inverter. In addition, the value of maximum output voltage in Figure 4 is expected considering the arrangement of modules (parallel and series arrays and strings) and maximum power voltage of each module (check Table 1 for modules' specification). Figure 5 shows the total radiation incident on the system where the maximum solar radiation exceeds 1000 W/m^2 for the whole sixty days of data collecting. This is expected during the summer season in Jordan. Comparing the behavior of current, voltage, and incident radiation, we notice that the output voltage is almost constant within a certain range and transition from ON state to OFF state is abrupt (inverter passes no voltage below a certain threshold), while the current goes from minimum value (zero or very small value) to a maximum gradually in a direct relationship with incident solar radiation. The values in Figures 3, 4, and 5 are used to calculate instantaneous efficiency for the whole system considering total surface area of the thin-film modules, Figures 6. It is clear that instantaneous efficiency rises abruptly (due to jump in voltage values, Figure 4) at the beginning of every day, then it decreases slightly before it increases considerably at the end of each day with a maximum instantaneous efficiency of 8− 9.7%.

The average daily AC current, voltage, and incident solar radiation are shown in Figures 7, 8, and 9, respectively. The daily efficiency, Figure 10, agrees with reported values in several studies for other parts of the world, around 7%, [10, 11].

Due to the harsh environment at HU, its location near a major industrial and free-trade zone, and east of Jordan's main refinery, the modules were covered with accumulated dust, as pictured in Figure 11. After cleaning the system on Day 51 of the experiment, the daily efficiency increases from below 7% to above 7.5%, which translates to about 10% increase in the thin-film efficiency in converting solar radiation into AC power output per unit area. This increase in efficiency may be contributed to other factors other than dust such as cooling of modules. Further analysis is planned in the future.

Solar inverter efficiency (AC output power divided by DC input power) is calculated and shown in Figure 12. The inverter becomes switched on when voltage reaches a certain threshold and the instantaneous conversion efficiency jump to maximum of approximately 95%, which is below the maximum efficiency listed in tables of specifications for the inverter, Table 2. However the daily conversion efficiency is around 90%, Figure 13.

Increasing temperature has an adverse effect of the efficiency of the system (both for modules and inverter). Figure 14 shows variation of ambient and module temperatures for the 60 days of the experiment, and Figures 15 and 16 show the average daily ambient and module temperature, respectively, during the experiment.

The wind speed during the experiment, which was recorded and daily averaged, is shown in Figure 17. The values indicate that the wind speed is within the expected range in Jordan for this time of year.

The correlation between dust, wind, and ambient and modules temperature with the system efficiency will be the heart of the next study after acquiring sufficient data over all the seasons of the year.

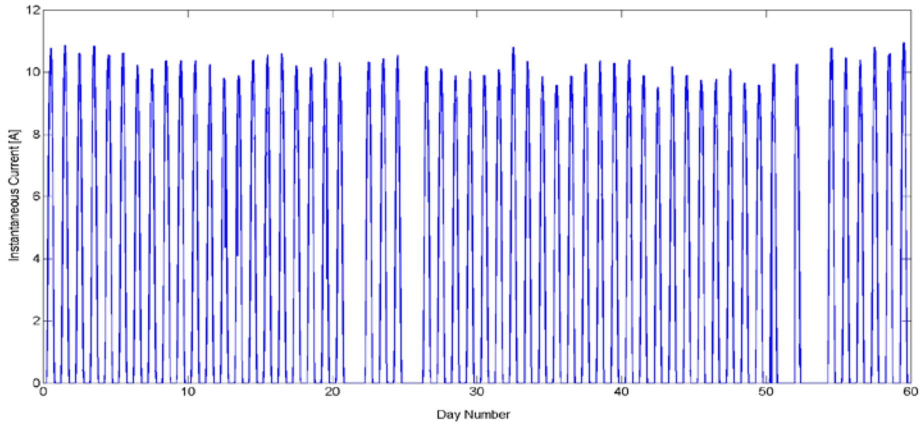

Figure 3. Instantaneous AC currect supplied to the grid

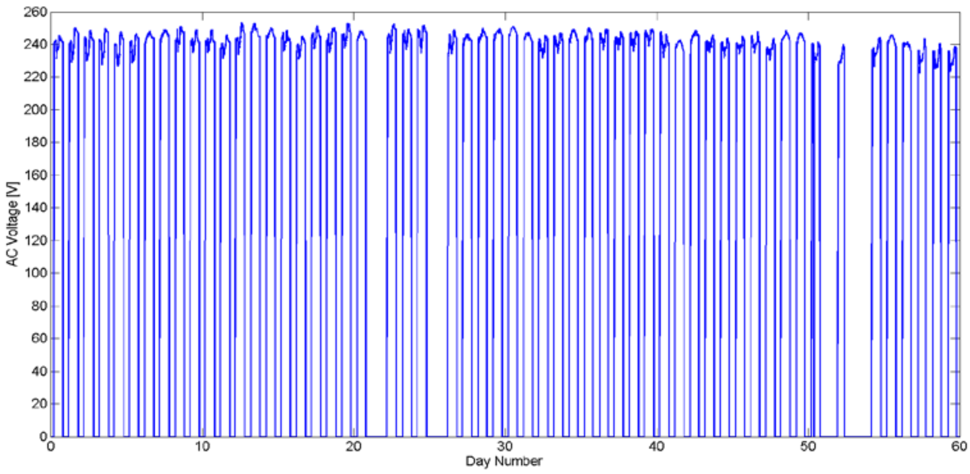

Figure 4. Instantaneous voltage supplied to the grid

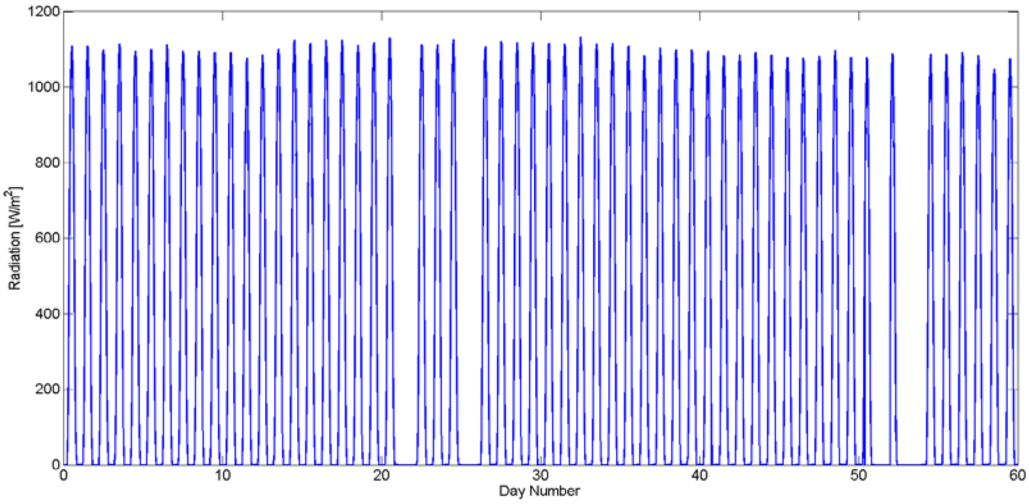

Figure 5. Instantaneous total solar radiation incident on system

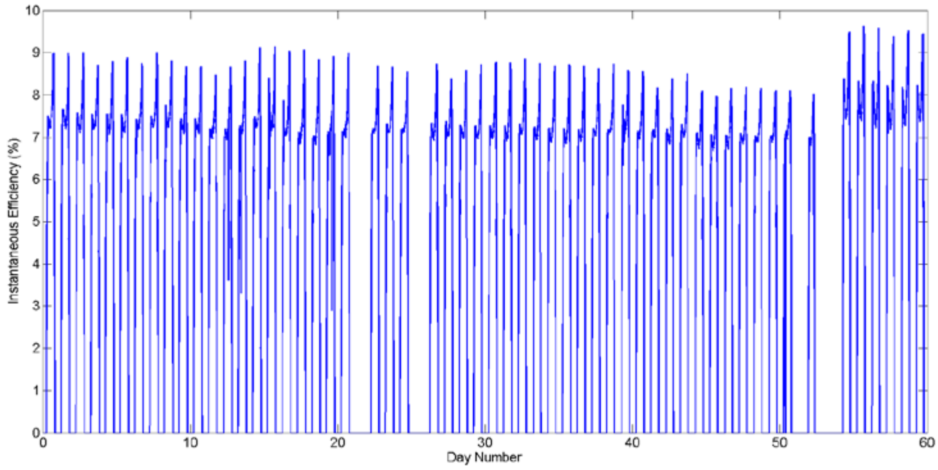

Figure 6. Instantaneous efficieny for the whole system

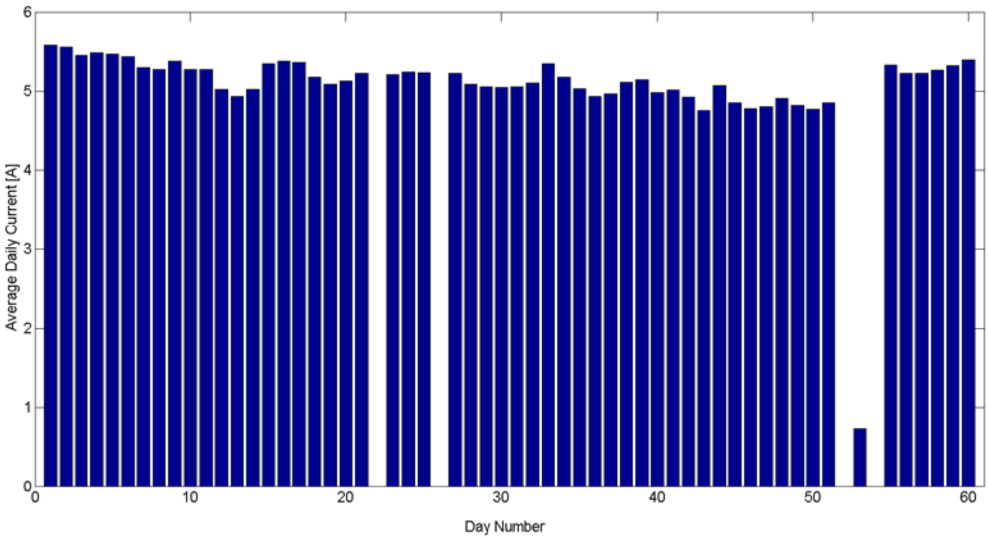

Figure 7. Average daily AC current supplied to the grid

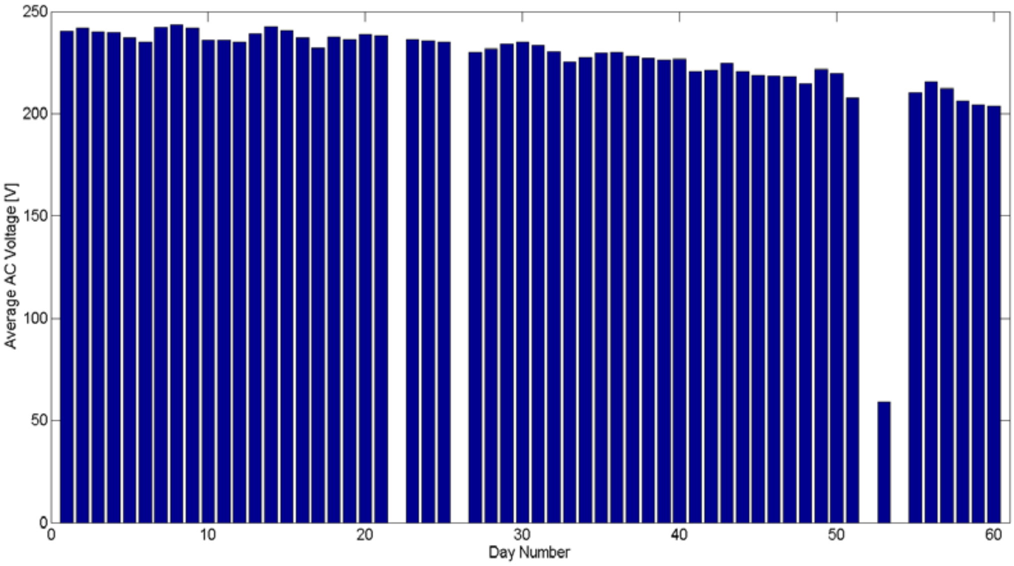

Figure 8. Average daily AC voltage supplied to the grid

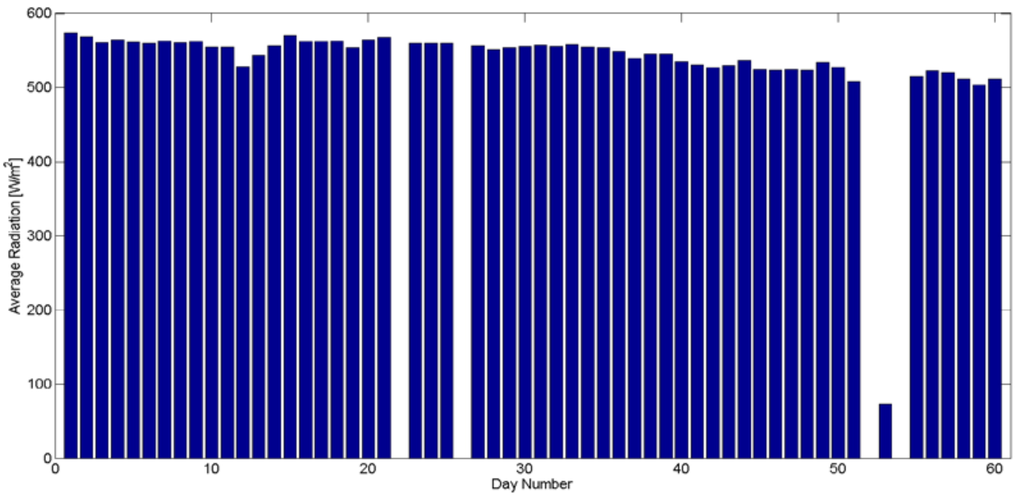

Figure 9. Average daily total solar radiation incident on system

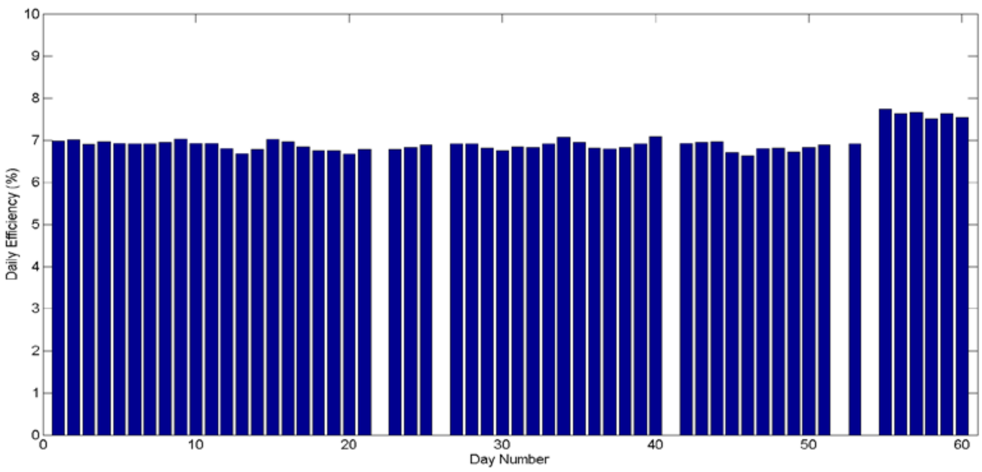

Figure 10. Daily efficiency for the whole system

Figure 11. System is covered with dust (picture taken after 45 days from running the system)

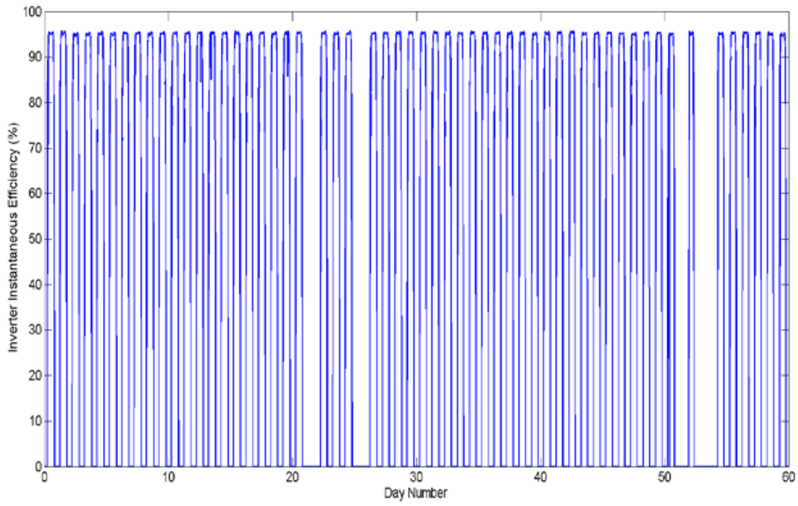

Figure 12.Instantaneous efficiency of the solar inverter

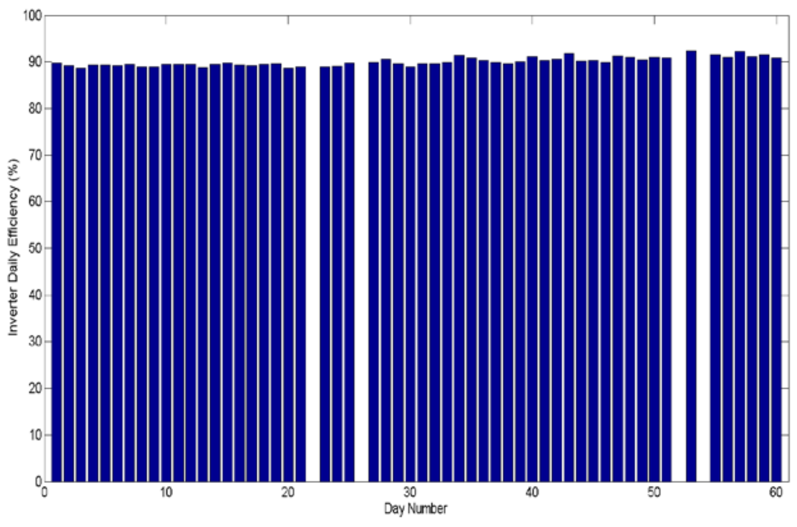

Figure 13: Daily efficiency of the solar inverter

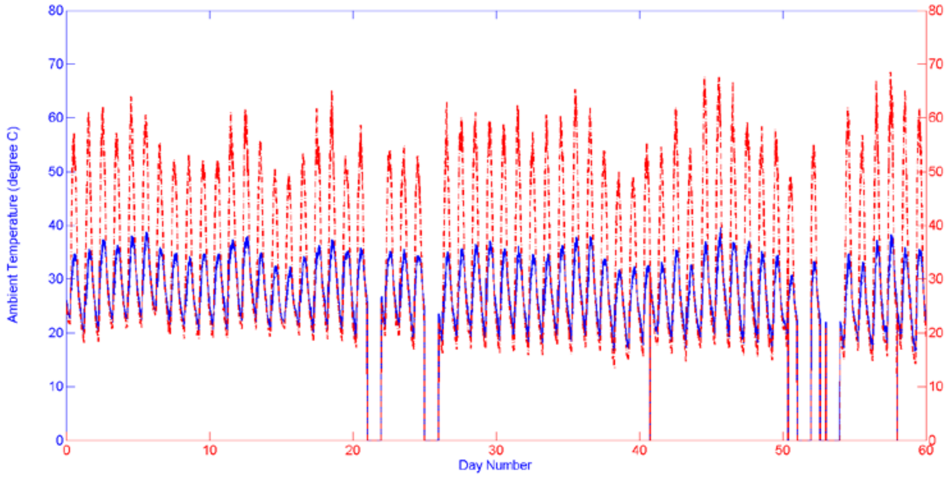

Figure 14. Variation of ambient (blue color) and module (red color) temperatures

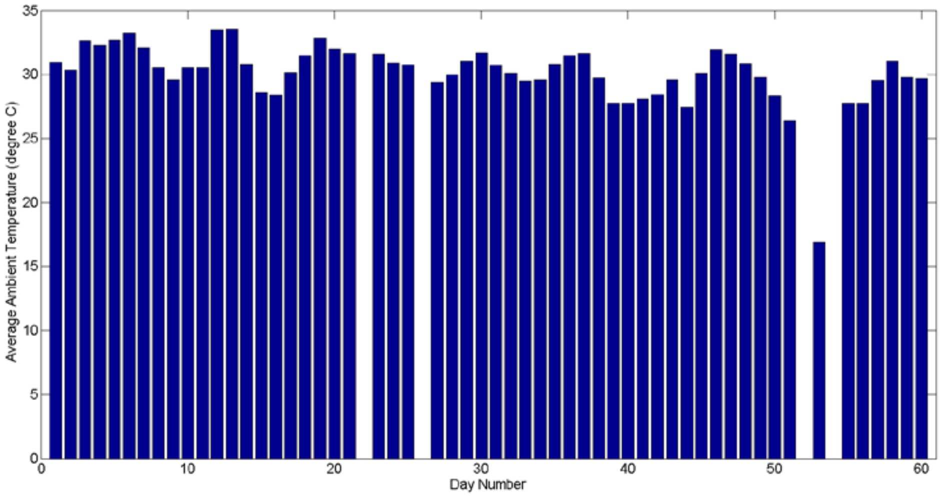

Figure 15. Average ambient temperature

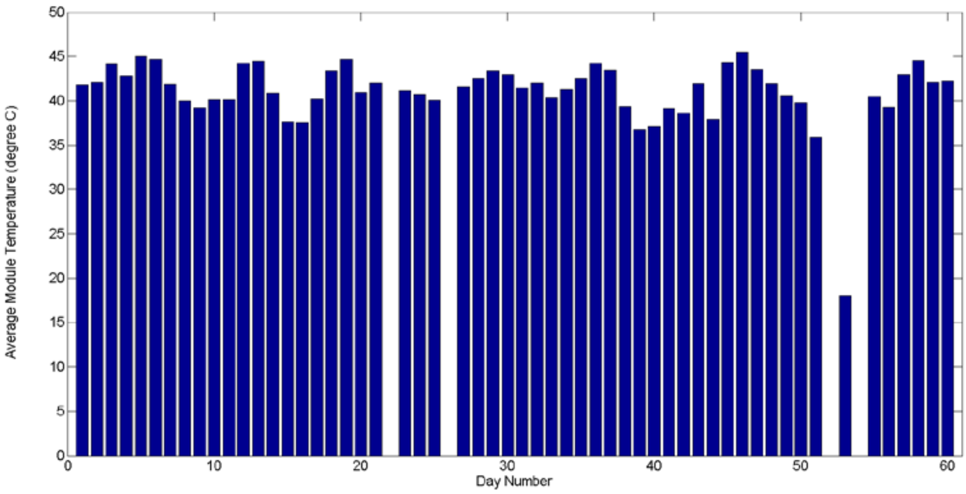

Figure 16. Average module temperature

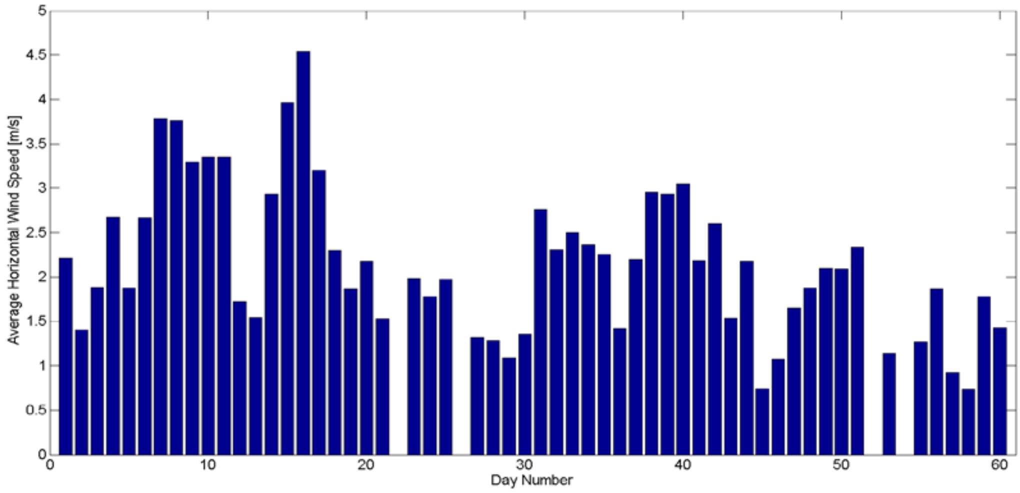

Figure 17. Average horizontal wind

5. Summary, conclusions, and Future Work

A thin-film PV system is installed and tested at the Hashemite University, Jordan. The system is fixed at near optimal orientation for the location selected and is connected to the local grid. The system constructed to function in part as a car parking that is utilized to increase thermal comfort in the harsh environment at the Hashemite University. We found that the instantaneous and average efficiencies are within the reported values from the manufacturer and other studies in different parts of the world. We plan in the near future to extend testing time to study the behavior of thin-film PV system over all seasons of the year. In doing so, we plan to carry out a feasibility study on the use of thin-film PV in Jordan.

The future installation and operation of PV plants as a step toward urban technology concept should be promoted in the Hashemite University by considering new criteria for the landscape integration of PV plants. The viewpoints from which the visual simulation of the PV plant should be taken are very important parameter. Other relevant parameters such as materials and color, land use, visual impact on the landscape, and glare should be considered to solve any future concerns of the users about the environmental, and landscape impacts of PV plants technology. At the university level, the future guidelines for the authorization of renewable energy plants should contain some new criteria for the landscape integration of PV plants and the visual simulations techniques.

Acknowledgments

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