Conference Presentation

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Performance Analysis of a Wearable Photovoltaic System

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Abstract—**This paper provides a performance analysis of a wearable photovoltaic system mounted on the outer surface of a backpack. Three types of photovoltaic materials, commonly used for electricity generation, have been investigated under various conditions including sun irradiance, angle-of-incidence and sun inclination. The results of the investigation have shown that the system equipped with the rigid mono-Si panels performs 3.5 to 4.9 times better than the system equipped with a-Si flexible PV modules. The average power generated by the wearable photovoltaic system is about 30% of the maximum installed power for any photovoltaic type. This paper presents the test data resulting from the evaluation of the daily energy production of a wearable photovoltaic power supply.**

Keywords—photovoltaic; wearable photovoltaic system; auxiliary power supply; efficiency

I. Introduction

Photovoltaic (PV) systems are widely used in many industrial and domestic installations to cover increasing demand in electrical energy by various power consumers. The scope of modern PV technology implementation is very wide – from low-power portable (PV-based auxiliary power supplies, “solar chargers”, etc.) and domestic PV applications to large-scale PV power plants. It has been reported that due to intensive growth of PV technologies over the past decades the global solar PV capacity has reached 300 GW at the end of year 2016 [1] where the flexible PV modules share around 8% [2]. Intensive price reduction of PV cells has made PV technology affordable for a variety of portable and wearable applications to provide electrical energy for autonomous and low-power loads. Unlike PV power plants, low-power portable and wearable PV systems usually utilise bidirectional dc-dc converters and energy storage in order to supply loads from both PV modules and charged batteries [3].

It has been noticed that over the past few years the wearable PV systems have attracted particular attention from engineers involved in the development of light weight renewable and autonomous power supplies. These systems are designed for tourists, military personnel, and emergency services [3]-[6] to provide electricity for portable or wearable electrical/electronic equipment and batteries using power obtained from the sun. However, due to the comparatively low efficiency of PV cells, the crucial issue of a wearable system design is the improvement of the PV based power supply performance.

The most important factors affecting the performance of PV systems are the solar irradiance level at the photosensitive surface and the temperature of the PV modules. A higher irradiance level (and/or lower cell temperature) causes more energy to be produced by the photovoltaic modules. However, the actual efficiency and power generation depend on the angle-of-incidence of the solar rays on the PV modules. This angle is a crucial parameter for energy generation forecasting because it causes losses related to non-optimal oriented PV systems (so called “cosine” losses) and additional optical losses in the glass or other protective material, covering the PV surface. It is difficult to make an analytical prediction of the irradiance-to-power performance taking into account the angle-of-incidence for different types of photovoltaic modules, although several approaches based on the equivalent circuit or point-value model [7] have provided adequate accuracy using empirical parameters [8]. The data obtained from experimental investigations showed that the optical losses can be neglected for an angle-of-incidence less than 55 degrees, but large angles lead to a significant drop in efficiency [8].

Aging of PV modules also causes a decrease in power generation. According to typical PV module datasheets, the maximum module permanent degradation is around 10% for the first 10 years and around 20% over 25 years. Experimental investigation shows that the degradation rate can vary from 0 to 5% per year with a median value of 0.5% per year for Si- and 1.0% for thin-film PV modules [9]. Taking into account series and parallel connections of separate modules in PV systems, different degradation rates lead to a decrease in PV system performance [10], [11]. The performance of such systems also depends on the material of the photovoltaic module. Many papers [12]-[14] provide analyses of variations in the energy efficiency of different photovoltaic materials (mono- and poly-Silicon, amorphous Silicon, etc.) under varying environmental parameters using simulation models. In addition, performance characteristics of different materials are non-linear to solar irradiance, especially for low-light cases (shadow, cloud weather, etc.). The design and manufacture of photovoltaic materials with improved efficiency for non-optimal conditions is an important issue for portable and wearable PV systems [4].

This paper discusses the performance analysis of the power generation of wearable backpack-mounted PV systems utilising the most common types of low-power PV modules represented in the market. The analysis is based on data obtained from experiments with different PV cells and presents calculations of the power generated by the systems operating under varying orientations.

II. Wearable PV System

Three types of PV modules used in the wearable application have been tested: Amorphous Silicon (a-Si) flexible thin-film, Poly-crystalline Silicon (Poly-Si) semi-flexible and Mono-crystalline Silicon (Mono-Si) rigid PV modules. The Amorphous Silicon PV module [15] is one of the best solutions for portable and wearable applications due to its mechanical flexibility, ability to collect more energy under low-light condition, and its lower temperature sensitivity compared to other PV technologies. Photovoltaics based on Poly- or Mono-crystalline Silicon have better efficiency compared to amorphous panels. This is why such

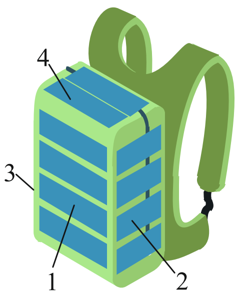

Fig. 1. Placement of PV modules on backpack for portable auxiliary PV power supply.

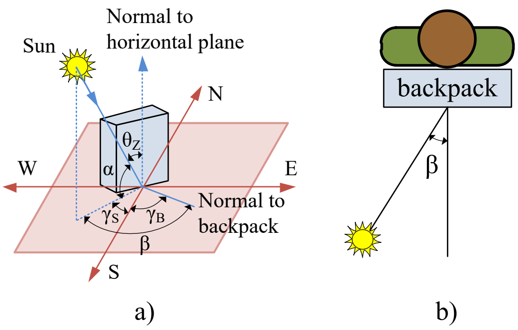

Fig. 2. Angles in portable PV system placed on backpack: isometric view (a), top view (b).

TABLE I. PV Modules Characteristics

Parameter	Type of PV module		
	Flexible Thin-film a-Si	***Rigid Mono-Si***	***Semi-Flex Poly-Si***
Width, mm	270	116	195
Height, mm	90	116	98
P_{max}, W	0.72	1.5	1.0
I_{SC}, mA	125	275	850
V_{OC}, V	10.5	7.2	2.0
PV area, mm	238x73	18x52	160x78
PV square, cm^2	173.7	112.3	124.8
Number of PV	1	12	1
Weight, g	8.5	65.0	40.0

types of PV are widely used in large-scale PV plants. Unlike a -Si, classical Poly-Si and Mono-Si modules are difficult to implement in the flexible form.

The performance of PV modules mounted on the outer surface of the backpack as shown in Fig. 1 have been analysed under three different light conditions (cases):

- Case 1. Direct light with optimal PV orientation towards the sun. The case represents situations in which the side of the backpack is oriented to the sun and the angle between an imaginary line normal to the PV surface and the solar rays is less than 30°.
- Case 2. Direct light with non-optimal PV orientation. This case is possible when side of backpack is illuminated by the sun and the angle between the normal to the PV surface and the solar rays is more than 30°.
- Case 3. Diffuse light. This case represents shadowing of the PV modules by a person wearing a backpack with the PV modules installed.

It should be noted that the PV modules can be mounted on different sides of the backpack so that the panels will be illuminated differently depending on the sun's position, backpack orientation and the placement of PV panel on backpack. PV modules can be placed in four different positions: front, right, left and top side of the backpack (1, 2, 3, and 4 respectively as shown in Fig. 1).

The efficiency and power generation of such PV placement depend on the PV module's *P-V* characteristics, sun irradiance level for the current weather conditions, sun inclination angle (angle α in Fig. 2) and the angle between the

TABLE II. PV Modules Temperature During the Experiment

Temperature, °C	Type of PV module		
	Flexible Thin-film a-Si	***Rigid Mono-Si***	***Semi-Flex Poly-Si***
C1	69.4	70.3	72.5
C2	63.7	64.2	65.3
C3	56.5	57.7	58.8

horizontal projection of the sun's rays and the datum line normal to the front backpack surface (angle β in Fig. 5). γ_S and γ_B are solar and normal to backpack azimuth angles, respectively.

Very often the technical information, offered in the market on PV modules, is incomplete (absent temperature coefficients, *I-V* or *P-V* characteristics, etc.). For this reason an experimental investigation was performed on the PV modules in order to obtain *I-V* and *P-V* characteristics which were then applied to their further analysis.

III. Experimental Evaluation of PV Module Parameters

The experiments to evaluate PV module parameters have been conducted in the city of Chernigiv, Ukraine (coordinates 51°30′0″N 31°18′0″E) on July 31, 2017. All of the PV panels were tested for three different conditions: photosensitive surface perpendicular for the sun rays, parallel to the Earth surface, parallel to the sun rays (C1, C2 and C3 in Table II, respectively). The solar irradiance for all of the experiments was measured with a photo-resistive sensor and was determined to be equal to 950 W/m^2 (a good, sunny day without clouds). The temperature of all of the PV modules was measured with a non-contact infrared thermometer GM550 and the resulting experimental data is presented in Table II for an air temperature of 29°C.

Table III. Experimental Parameters of PV Modules

Parameter	Type of PV module		
	Flexible Thin-film A-Si	***Rigid Mono-Si***	***Semi-Flex Poly-Si***
P_{MPP}^{C1}, mW	571.9	1158.4	868.5
P_{MPP}^{C2}, mW	325.5	870.9	670.1
P_{MPP}^{C3}, mW	30.9	61.5	36.5
$P_{MPP}^{C3}/P_{MPP}^{C1}$, %	5.4	5.3	4.2

The first case (C1) represents the most efficient placement of PV modules and the maximum power generation. The second case (C2) represents the situation when the PV module is not-optimally oriented towards the sun thus causing a decrease in power generation. Both of these experiments estimate the influence of the direct sun light on the electrical power production of the PV modules. The third case (C3) deals with diffuse sun light, reflected in the Earth's atmosphere from clouds, air molecules, etc. This experiment represents real weather conditions when the PV module is used in sunny weather but fully shadowed by obstacles, or the PV module is directed in the opposite direction to the sun.

Each experiment records the voltage and current from the PV module for varying resistive electric load, from open-circuit to short-circuit. Two digital Mustech multi-meters have been used to provide high precision measurement readings.

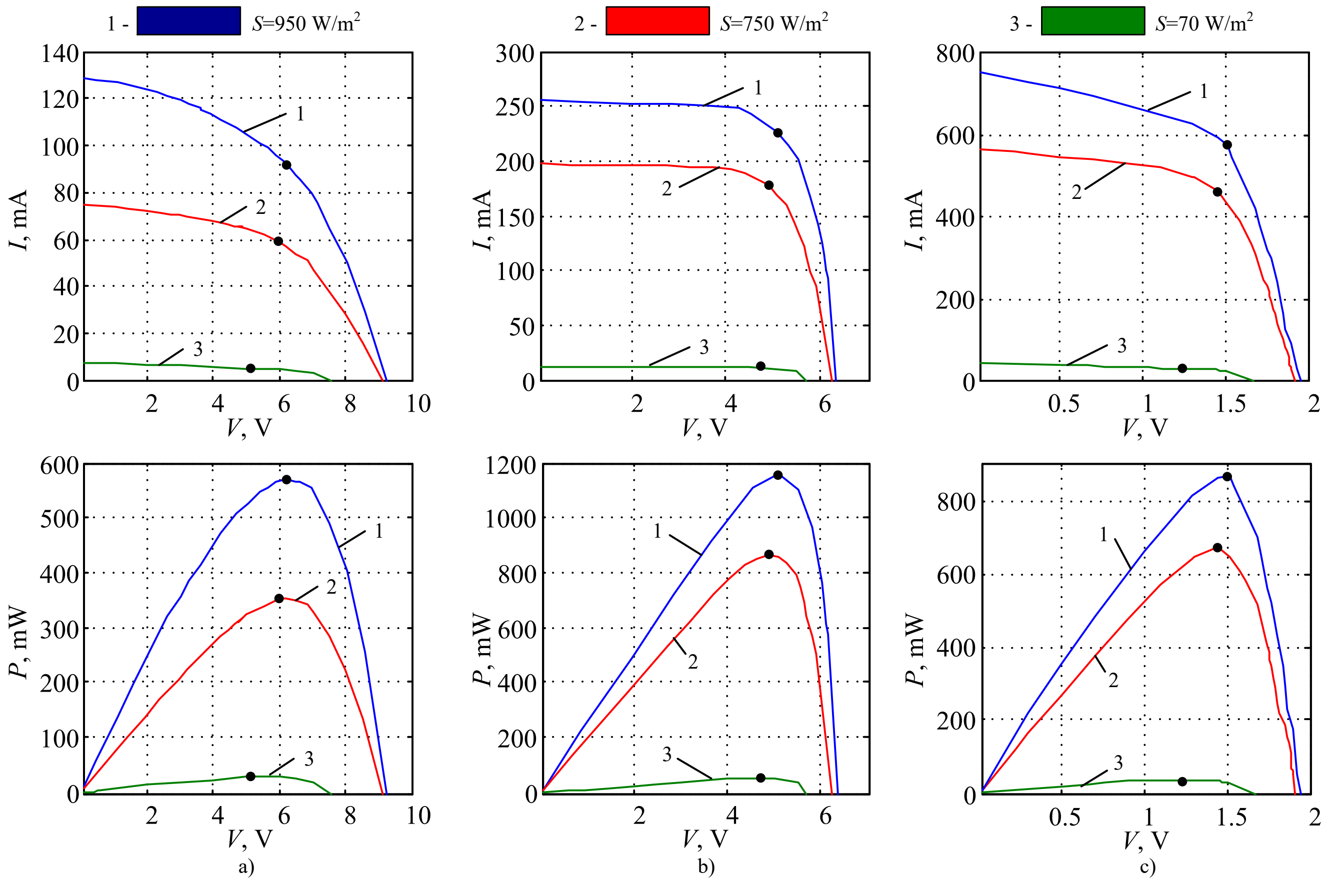

Fig. 3. Experimental V-I and P-V characteristics of different PV modules: flexible thin-film amorphous Si (a), rigid mono-crystalline Si (b), semi-flexible poly-crystalline Si (c).

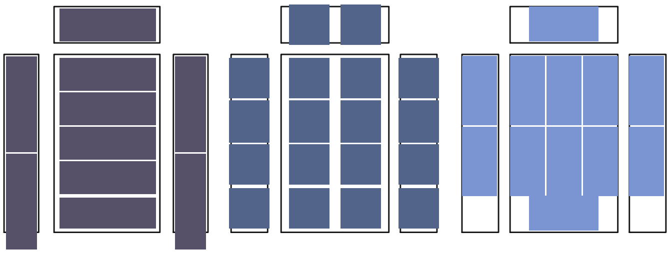

Fig. 4. Placement of different PV modules for portable auxiliary PV power supply: flexible thin-film amorphous Si (a), rigid mono-crystalline Si (b), semi-flexible poly-crystalline Si (c).

Experimental *V-I* and *P-V* curves of three PV modules (flexible a-Si, Rigid Mono-Si and Semi-flexible Poly-Si) are represented in Fig. 3 where curves 1, 2, 3 are corresponding to the cases C1, C2, C3 mentioned above. Each *V-I* curve looks typical and consists of a constant current (current source), maximum power point and constant voltage (voltage source) regions. It has been seen that the flexible and semi-flexible PV curves have a slight slope in the current source region compared to the rigid modules where the characteristic is flat. This means that the flexible PV structure has greater internal resistance R_S which leads to a decrease in efficiency. The most important part of each *P-V* curve is the maximum power point P_{MPP}^{Cx}, highlighted in Fig. 3 by a dot, where C_x is a case number. Ratio P_{MPP}^{C3} to P_{MPP}^{C1} shows relative efficiency of the PV module for low level irradiances.

The data analysis in Table III confirms the statement that a -Si PV has better efficiency for low-light cases. However, this is only correct for comparisons made amongst similar semi-flexible Si modules, whereas the relative efficiency of the tested rigid Si module is almost the same as the a-Si PV module. It should be noted that the questions of energy harvesting from PV is outside the scope of this article and has already been analysed in many other publications.

IV. Estimation of Power of Wearable PV System

As mentioned above, the power generated by a wearable PV system depends on the placement of the PV modules, the sun's position and the orientation of PV system. The analysed wearable PV system was placed on a 15-liter backpack with the dimensions: height 0.5 m, width 0.3 m, depth 0.1 m. The frontal area (1 in Fig. 1) is 0.15 m^2, the right and left side areas (2 and 3 in Fig. 1) – are both 0.05 m^2, and the top surface area is (4 in Fig. 1) – 0.03 m^2. Taking into account the size and shape of the PV modules tested (Table I), the wearable system can be mounted on a backpack as shown in Fig. 4 covering all available sides of the backpack. It can be clearly seen that the covered area is almost the same for various types of PV modules neglecting differences in modules size. The weight of the PV system is 85 g (flexible Thin-film a-Si), 1170 g (rigid Mono Si) or 480 g (Semi-flexible Poly Si).

The maximum power point for the wearable PV system has been determined in terms of P_{MAX} where P_{MAX1} = 7.2 W for flexible thin-film amorphous Si, P_{MAX2} = 27 W for rigid mono-crystalline Si and P_{MAX3} = 12 W for semi-flexible poly-crystalline Si modules. These values correspond to the reference irradiance and temperature (1000 W/m^2 and 25°C) and the optimal orientation of all PV modules. Realistic generation patterns for different angles α and β are shown in Fig. 5. The patterns represent isometric views from the front side of backpack. Number 1…4 coincides with the same numbers in Fig. 1. It should be noted that these patterns are valid for worn backpacks. Obviously, all surfaces of a backpack cannot be simultaneously optimally oriented to the

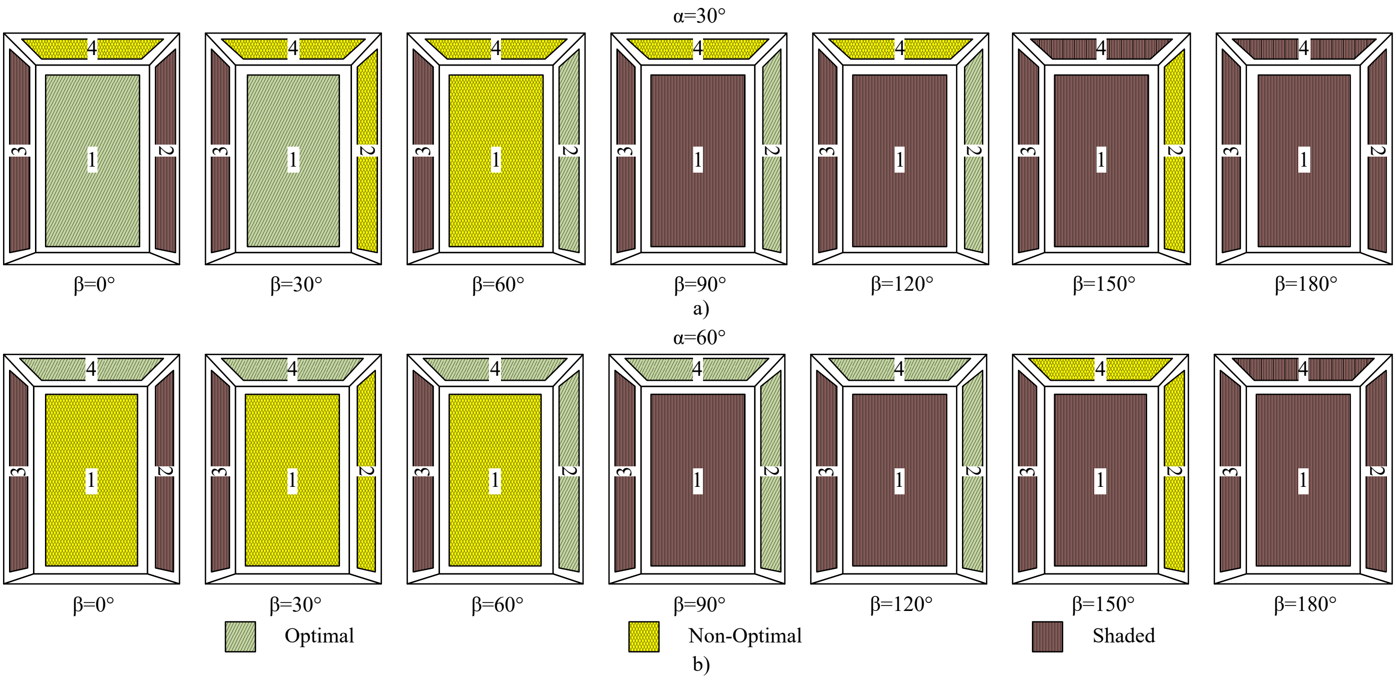

Fig. 5. Orientation of PV modules on backpack sides for different β angles: in case of α = 30° (a), α = 60° (b).

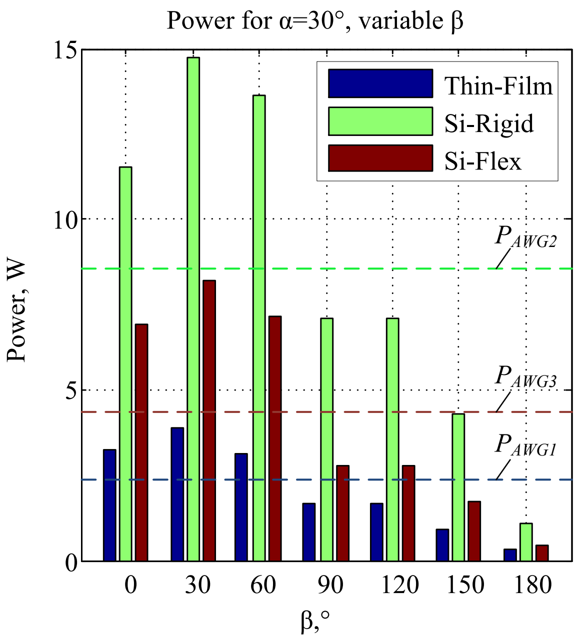

Fig. 6. Portable PV power supply power generation for different PV modules for α = 30°.

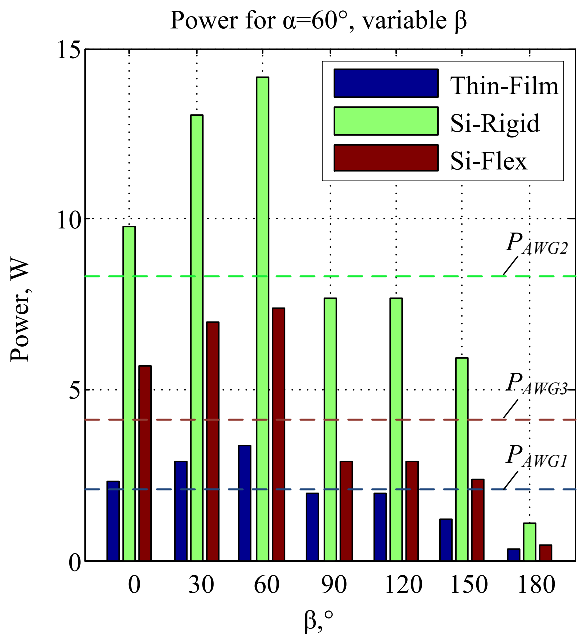

Fig. 7. Portable PV power supply power generation for different PV modules for α = 60°.

sun. Comparison of α = 30° with α = 60° shows that the second case has more optimally oriented sides (left 2 and top 4), but the total area of the sides is less than the front side. *V-P* curves and the maximum power points obtained in the previous section help to calculate the power generation of the test PV system for all of the cases shown in Fig. 5.

Optimally oriented modules have *P-V* curves marked as 1 in Fig. 3, non-optimally oriented as 2, and shaded modules as 3. The total power of the wearable PV system on the backpack is calculated as following:

$$P_{PV_x} = \sum_{i=1}^{4} n_i \times P_{MPP_i} \quad (1)$$

where P_{PVx} – total power for type of PV panel PV_x (W); n_i – number of PV panels mounted on *i* side; P_{MPPi} – maximum power point for PV modules on *i* side (W). Type of PV panel is 1 for flexible thin-film amorphous Si, 2 for rigid mono-crystalline Si and 3 for semi-flexible poly-crystalline Si.

The results of the analysis performed for all of the generating patterns shown in Fig. 5 are represented in Fig. 6 and Fig. 7 for α = 30° and α = 60° respectively. Analysis of the data reveals the following patterns:

- Total power for wearable PV system based on a-Si flexible PV modules is in 3.5 to 4.9 times less compared to rigid mono-Si and in 1.4 to 2.5 times less compared to semi-flexible Poly-Si for the same area covered by PV modules.
- Total power for semi-flexible Poly-Si is in 1.7 to 2.6 times less compared to rigid mono-Si.
- The sun's inclination angle α has little effect on the total power of the PV system. The average power P_{AVGx} (for a probable backpack azimuth angle β) is 2.1W/2.0W for A-Si, 8.5W/8.4W for rigid mono-Si, 4.3W/4.1W for semi-flexible poly-Si. The nominator number refers to α = 30° and denominator to α = 60°. The higher power for α = 30° is explained by the higher frontal area of the backpack and its better illumination under lower sun irradiance.
- A-Si flexible PV modules have a better relative efficiency for shaded panels (β = 180°) P_{PV1}/P_{MAX1} = 4.17% whereas P_{PV2}/P_{MAX2} = 4.07% and P_{PV3}/P_{MAX3} = 3.60%.

V. Conclusion

Experimental investigation and analysis has demonstrated that the electrical power generated by a wearable PV system based on flexible thin-film amorphous Si or semi-flexible poly -crystalline Si PV panels is 1.7 to 4.9 times less when compared to the rigid mono-crystalline Si modules. The declared better efficiency of a-Si panels has been proved. However, under real conditions, the additional gain in efficiency of the shaded a-Si PV did not compensate a significant reduction in its overall efficiency compared to any poly- or mono-Si modules. The average power generated by any of the wearable PV systems analysed is about 30% of the maximum installed power (for the probable orientation of the worn backpack and a solar irradiance S = 1000 W/m^2).

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