IoT IN EDUCATION - PHOTOVOLTAIC PANEL SYSTEMS

Marin OPREA[1], Mariana MOCANU[2]

In this paper we presented a synthesis of the design, construction and implementation activities, at the school level, of an intelligent system for transforming solar energy into electricity based on photovoltaic panels, with the possibility of real-time monitoring, via Internet, of its functional parameters: voltage (U), current (I), power (P) and electrical energy (W) produced. Since the purpose of the project was educational, we started the activities with the design and realization of a didactic solar panel, composed of polycrystalline solar cells. To determine its functional parameters, we used an experimental method different from the classical method (based on measurements made with multimeters). This new method was based on the INA219 current-voltage sensor connected to an Arduino Uno board and allowed real-time representation of the I-U and P-U characteristics of the panel using the Excel add-in Data Streamer. The technical parameters of the panel were studied in different lighting conditions (artificial light and natural light). After the realization and functional testing of this didactic panel, we included in the scope of the experimental activities some solar panels of commercial origin, of low and medium power. These activities prepared the framework for the realization of an IoT monitored photovoltaic system. The functional parameters of the panel were monitored through the open source IoT platform - ThingSpeak. The remote control of the consumers was realized both via Bluetooth and WiFi connection.

Keywords: solar cells, photovoltaic panels, current-voltage characteristics, date streaming, sensors, IoT platform

1. Introduction

Human society has entered a new stage of development, becoming a society of information and knowledge [1] marked by a complex and profound dynamism, requiring a large consumption of energy [2]. In this context, the world's energy reserves, based on fossil fuels (coal, oil, natural gas), are continuously decreasing [3]. By default, the price of these fuels is getting higher and higher. Consequently, renewable energy sources (solar, wind, tidal, geothermal) have become a necessity for the functioning of modern society [4]. These non-polluting sources support global efforts to reduce the negative effects of climate change, making a major contribution to reducing greenhouse gas emissions [5]. Researchers in interdisciplinary fields are currently focused on the development of materials, devices and systems that allow maximum efficiency of the conversion of these alternative energies into electrical energy [6]. In the context of this transition of our

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society towards an energy future based on renewable resources, our students must know and understand the principles and technologies of converting these types of clean energy into electricity [7]. Thus, we initiated an interdisciplinary STEM project: Green Energy in Schools - IoT Monitored Photovoltaic Panel Systems [8-9]. Besides the didactic aspect, another very important reason for developing such a project was determined by the fact that the geographical area in which we undertook this endeavor is solarized for most of the calendar year.

2. Description of basic system components

A matrix array of solar cells constitutes a photovoltaic solar panel. Traditional solar panels have an efficiency of about 15-20%, which means they can convert 15-20% of the captured solar energy into electricity. In recent years there have been significant improvements in solar cell efficiency, with some newer technologies achieving efficiencies of over 25% [10-11]. Included in the category of these new technologies are: thin-film solar panels, transparent solar panels, perovskite-based solar panels, bifacial solar panels.

Depending on the electrical power developed, there is a wide range of such devices, divided into three large categories. In the first category we find mini-panels or low-power panels, used for charging mobile phones, some batteries (powerbank type), powering some garden lights (with LEDs) etc. The second category includes medium power panels used for LED night lighting, powering portable devices (smartphone, tablet, laptop), powering monitoring devices (CCTV video cameras, weather stations, optical beacons) etc.

Finally, the third category contains the high-power panels used for public lighting, for automatic water pumps used in irrigation, for the operation of electrical household appliances (apartment heating plants, refrigerators, TVs, PCs, economical light bulbs) etc. The parameters of a photovoltaic panel are: open circuit voltage (Uoc), short circuit current Isc, maximum power point (MPP), fill factor (FF) and energy efficiency (η). The parameters and the current-voltage (I-U) and power-voltage (P-U) characteristics associated with a photovoltaic panel can be viewed in Fig 1.

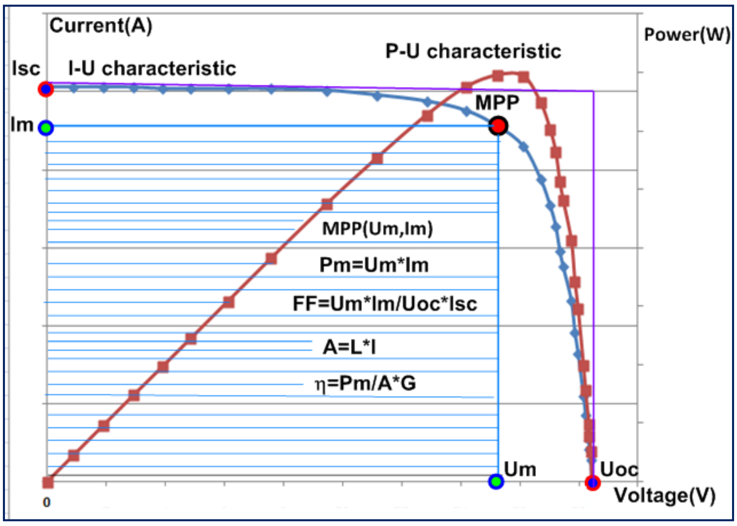


Fig. 1. Solar panel parameters (Uoc, Isc, MPP, FF, η) and characteristics (I-U/ P-U)

3. Design and implementation of the solar panel

The experimental activities carried out with the group of students participating in the project Green Energy in Schools - Photovoltaic Panels, were focused on the design and realization of a didactic solar panel.

We used a kit containing eight polycrystalline silicon solar cells. These cells have acceptable photovoltaic conversion efficiency (11%) and a moderate price. Comparatively, monocrystalline Si cells have a much better conversion efficiency (17%) but also a relatively high price. Fig. 2 presents a solar cell contained in the purchased kit.

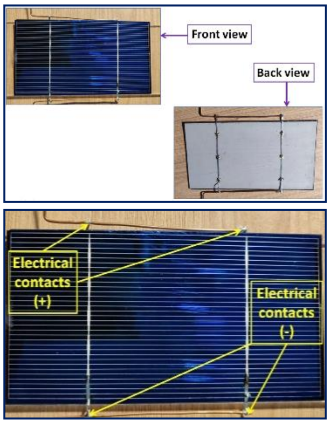


Fig. 2. Polycrystalline Si solar cell

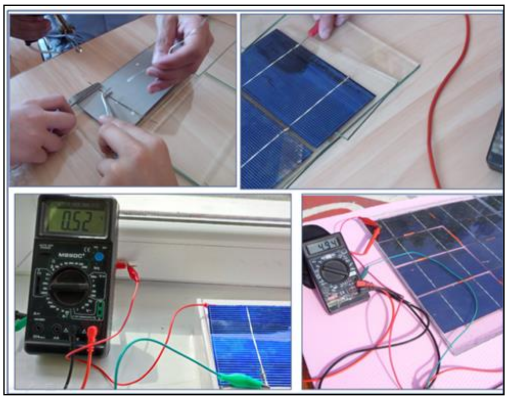


Fig. 3. Solar panel construction

The area of the cell is (15x8)cm^2, the thickness is 0.2mm and the mass is 6 grams. Under standard test conditions (solar irradiance G=1000W/m^2, temperature t=25°C, air mass coefficient AM=1.5) this device generates a power of 1.5W

(0.5Vx3A). During the assembly of the solar panel, we checked the electrical continuity and measured the electrical voltage produced (Fig. 3). The group of cells connected in series was sealed between two waterproof acrylic panels.

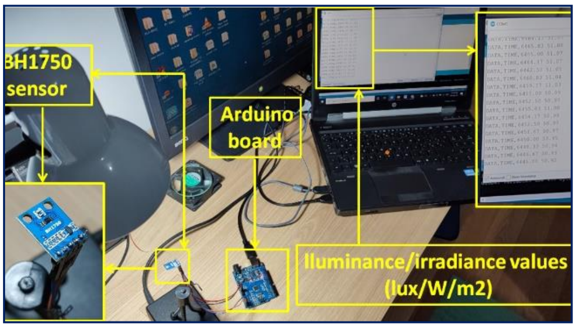


Fig. 4a. Experimental setup illuminace measurement

```
#include <Wire.h>
#include <BH1750.h>
BH1750 lightMeter;
void setup(){
  Serial.begin(9600);
  // Initialize the I2C bus (BH1750 library
  Wire.begin();
  // On esp8266 you can select SCL and SDA
  // For Wemos / Lolin D1 Mini Pro and the
  lightMeter.begin();
  Serial.println(F("BH1750 Test begin"));
}
void loop() {
  float lux = lightMeter.readLightLevel();
  float irr = (lux*0.0079);
  Serial.println(irr);
  delay(1000);
}
```

Fig. 4b. Arduino code

We determined the level of illuminance in the ambient environment using the light intensity sensor BH1750. It can be powered with a voltage between 3.3÷5V, offers a digital output signal, has a measurement range of 1÷65535lux and a precision of 1lux. We connected the sensor to an Arduino Uno board (Fig. 4a) programmed as in Fig. 4b and monitored the results using the Data Streamer add-in for Excel (Fig. 5).

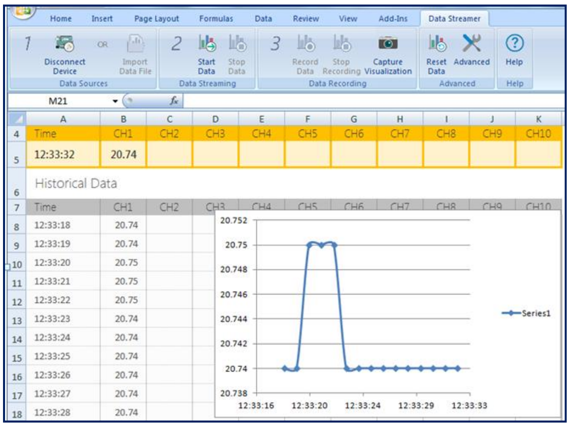


Fig. 5. Monitoring of lighting level

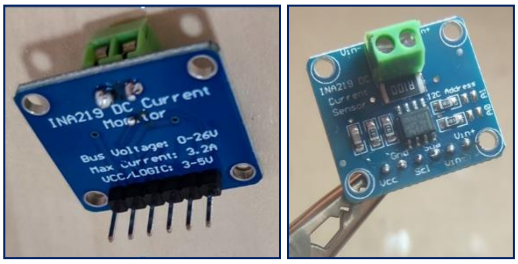


Fig. 6 - INA219 sensor module

This app allows users to visualize and analyze real-time data in Microsoft Excel. With Data Streamer, users can create dynamic dashboards, monitor live data feeds, and perform real-time calculations and analysis within Excel. The upper area of the app interface includes several buttons that provide functionality for managing data connections, viewing data and performing various tasks: Connect a Device, Import Data File, Start Data, Stop Data, Record Data, Stop Recording, Capture

Visualizations, Reset Data, etc. Data channels recorded numerical values and their real-time graphical representation occupies the rest of the interface.

The I-U and P-U characteristics of the panel were determined to establish the coordinates of the maximum power point MPP(Um,Im) with the help of an experimental setup based on an electronic module containing the INA219 current-voltage sensor (Fig. 6). The experimental setup and its electrical diagram are shown in Fig. 7a and Fig. 7b.

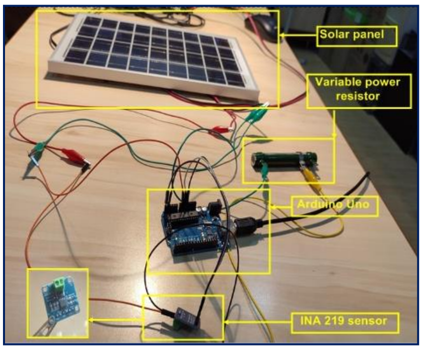


Fig. 7a. Experimental setup

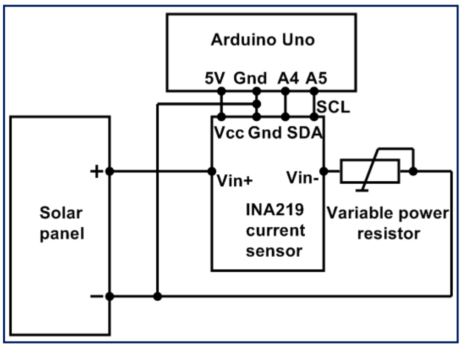


Fig. 7b. Electrical diagram

As can be seen from the wiring diagram, we connected the Vcc and Gnd pins of the sensor to the 5V and Gnd pins of the Arduino board, respectively. We also connected the SCL (Serial Clock Line) and SDA (Serial Data Line) pins of the sensor to the A4 and A5 pins of the Arduino board. The electrical terminals of the panel (+ and -) were connected with the Vin+ and Vin- pins of the sensor, respectively. Through the continuous variation of the electrical resistance of the power resistor (470Ω/50W) are obtained variations of the voltage and the electrical current in the circuit. After uploading the code to the Arduino board (Fig. 8) the experimental data transmitted by the sensor are processed and displayed in the Arduino Serial Monitor.

```
#include <Adafruit_INA219.h>

#include <Wire.h>
#include <Adafruit_INA219.h>
Adafruit_INA219 ina219;
 float voltage_V=0,shuntVoltage_mV,busVoltage_V;
 float current_mA = 0;
 float power_mW = 0;

void setup(void)
{
 Serial.begin(9600);

 uint32_t currentFrequency;
 ina219.begin();
 Serial.println("Measuring voltage and current with INA219");

}
```

```
void loop(void)
{
 getData();
 delay(1000);
}
void getData(){

busVoltage_V = ina219.getBusVoltage_V();
shuntVoltage_mV = ina219.getShuntVoltage_mV();
voltage_V = busVoltage_V + (shuntVoltage_mV / 1000);
current_mA = ina219.getCurrent_mA();
power_mW = ina219.getPower_mW();
power_mW=current_mA*voltage_V;


Serial.print(voltage_V);
 Serial.print(",");
Serial.print(current_mA);
 Serial.print(",");
Serial.println(power_mW);
}
```

Fig. 8. Sequences from the code uploaded on the Arduino

Alternatively, using the Data Streamer application, the experimental data stream can be sent for numerical and graphical visualization in Excel (Fig. 9).

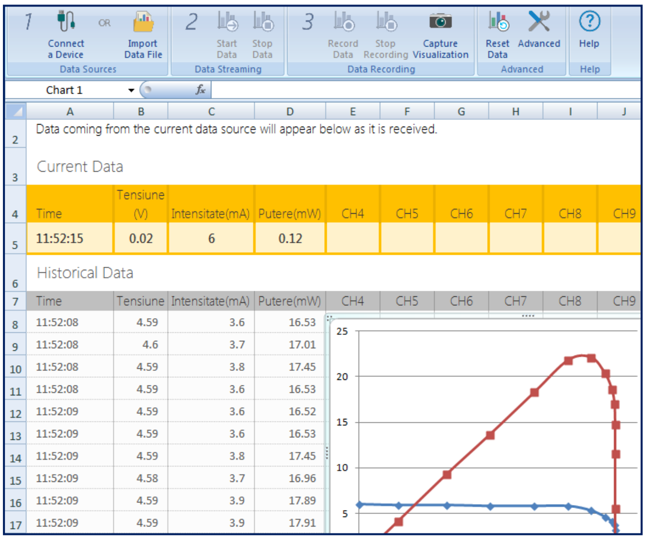
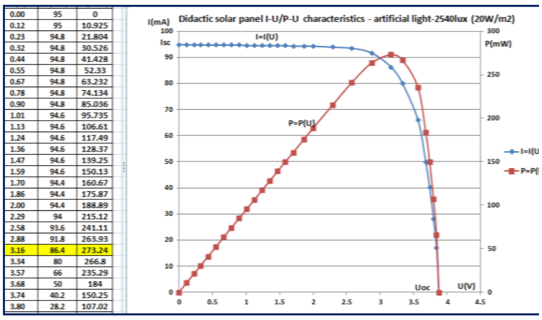


Fig. 9. Fast plotting of I-U/P-U solar panel characteristic in Microsoft Data Streamer

Fig. 10a presents the I-U/P-U characteristics (at 2540lux) obtained with the experimental setup shown previously. The technical parameters of the panel (Uoc, Isc, P_maxim(Pm), FF and η) can be observed in Fig. 10b.



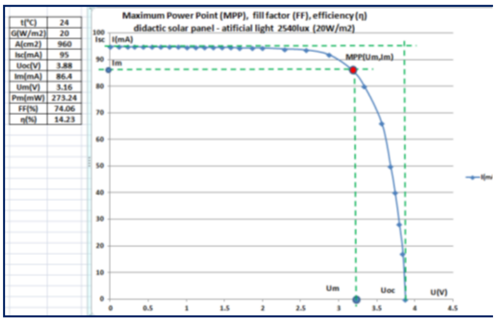


Fig. 10a. Laboratory characteristics of solar panel (2540lux)

Fig. 10b Technical parameters of solar panel in artificial light (2540 lux)

The characteristics using natural light (39370lux) are shown in Fig. 11a and the functional parameters of the panel are presented in Fig. 11b.

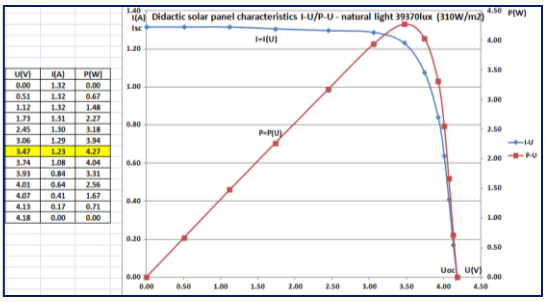


Fig. 11a. Characteristics I-U/P-U of didactic solar panel in natural light (39370 lux)

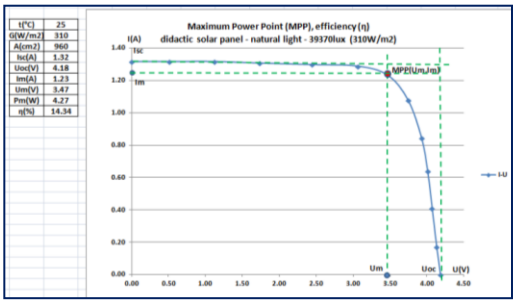


Fig. 11b. Technical parameters of didactic solar panel obtained in natural light (39370 lux)

As it can be seen from the previous graphs (Fig.10,11), under the conditions of an artificial illumination level of 2540lux, the point of maximum power (Pm=273.24mW) had the coordinates of MPP(Um=3.16V, Im=86.4mA). The open circuit voltage Uoc was 3.88V and the short circuit current had a value of Isc=95mA. The energy efficiency of the panel was 14.23%. At a natural illumination of 39370lux, the maximum power point reached the value of 4.27W and had MPP(Um=3.47V, Im=1.23A) coordinates. The open circuit voltage Uoc was 4.18V and the short circuit current had a value of Isc=1.32A. Under these conditions, the energy efficiency of the panel became 14.34%. These new values show how important is the level of illuminance to ensure a level of maximum power from a solar panel.

4. Experimental results

We determined the characteristics of the ***commercial solar panel (11x6) cm^2*** which can produce the power of 1W established in the standard test conditions (G=1000W/m^2, t=25°C, AM=1.5).

The technical parameters of the panel, respectively the I-U/P-U characteristics at an illumination of 1537lux can be seen in Fig. 12, and the results of the functional tests performed in natural light can be seen in Fig. 13.

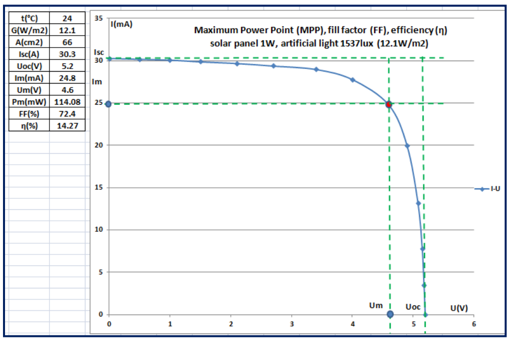


Fig. 12a. Technical parameters of solar panel (11x6)cm^2 (1537 lux)

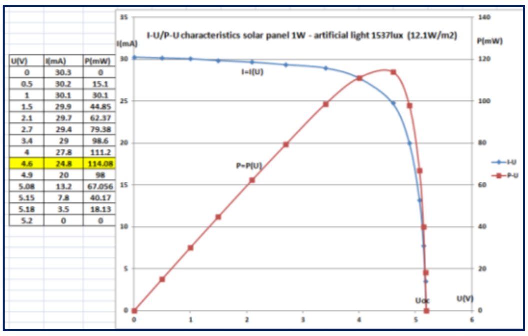


Fig. 12b. Laboratory characteristics I-U / P-U solar panel (11x6)cm^2 (1537 lux)

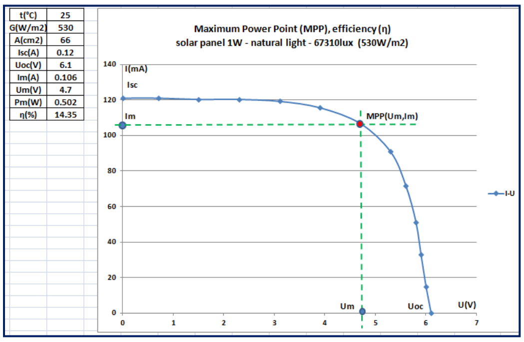


Fig. 13a. Technical parameters of solar panel (11x6)cm^2 in natural light (67310lux)

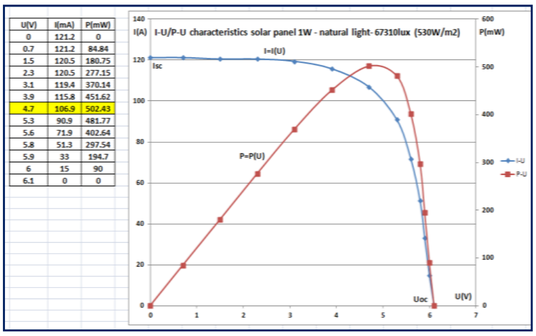


Fig. 13b. Characteristics I-U / P-U solar panel (11x6)cm^2 in natural light (67310lux)

As it can be seen from the respective graphs, the maximum power point (Pm=114.08mW) had MPP coordinates (Um=4.6V, Im=24.8mA), at an illumination of 1537lux. These values of Pm and Im registered important changes at an illumination of 67310lux, more precisely: 502.43mW respectively 106.9mA. We continued with the study of the energy efficiency of two other low-power solar panels: 1.25W and 1.5W. A comparison between the technical parameters of (11x8)cm^2/1W, (11x7)cm^2/1.25W and (11.5x8.5)cm^2/1.5W mini-solar panels in natural light is presented in Fig. 14.

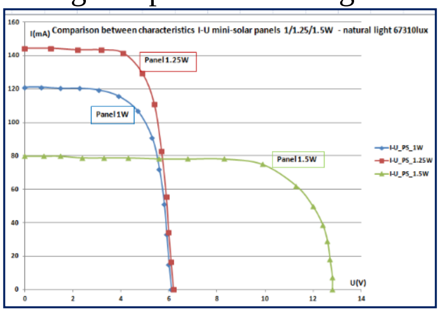


Fig. 14a. I-U characteristics comparison

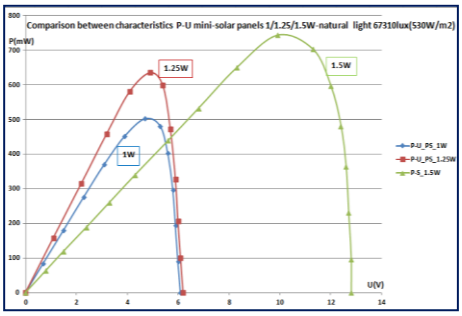


Fig. 14b. P-U characteristics comparison

From the previous graphs it can be seen that, while the 1W/1.25W panels generate the same Uoc voltage (approx. 6V), the 1.5W panel generates at least double the Uoc voltage (approx. 13V). The first two panels (1W/1.25W) have Isc currents relatively close in value, while the Isc current for the 1.5W panel is considerably lower. In these conditions, the 1W/1.25W panels can be used to ensure relatively high current intensities through the consumers, at relatively low operating voltages. In the case of the 1.25W panel, things are the other way around: it can ensure relatively high voltages on the consumers, under the conditions of a relatively small supply current. But the most important parameter that differentiates, in terms of energy efficiency, these panels is the maximum power supplied, Pm. We continued the experiments with ***medium power solar panels: 10W, 30W and 50W*** (Fig. 15a, Fig. 15b, Fig. 15c).

Fig. 15a. Solar panel 10W

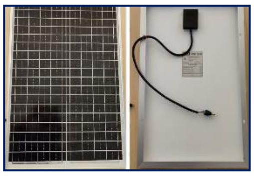
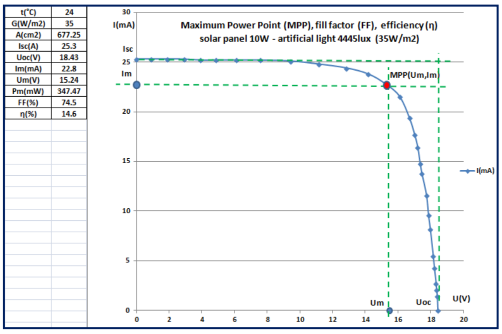


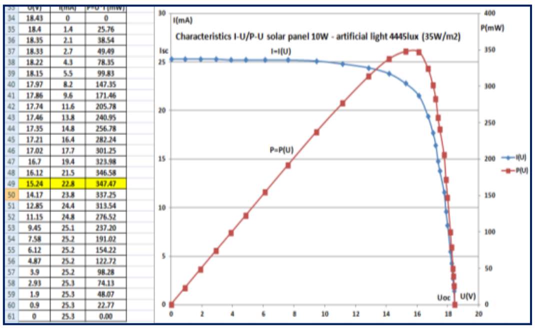
Fig. 15b. Solar panel 30W

Fig. 15c. Solar panel 50W



t(°C)	24
G(W/m2)	35
A(cm2)	677.25
Isc(A)	25.3
Uoc(V)	18.43
Im(mA)	22.8
Um(V)	15.24
Pm(mW)	347.47
FF(%)	74.5
η(%)	14.6

Fig. 16a. Technical parameters of solar panel 10W at 4445 lux



34	18.43	0	0
35	18.4	1.4	25.76
36	18.35	2.1	38.54
37	18.33	2.7	49.49
38	18.22	4.3	78.35
39	18.15	5.5	99.83
40	17.97	8.2	147.35
41	17.86	9.6	171.46
42	17.74	11.6	205.78
43	17.46	13.8	240.95
44	17.35	14.8	256.78
45	17.21	16.4	282.24
46	17.02	17.7	301.25
47	16.7	19.4	323.98
48	16.12	21.5	346.58
49	15.24	22.8	347.47
50	14.17	23.8	337.25
51	12.85	24.4	313.54
52	11.15	24.8	276.52
53	9.45	25.1	237.20
54	7.58	25.2	191.02
55	6.12	25.2	154.22
56	4.87	25.2	122.72
57	3.9	25.2	98.28
58	2.93	25.3	74.13
59	1.9	25.3	48.07
60	0.9	25.3	22.77
61	0	25.3	0.00

Fig. 16b. Characteristics I-U/P-U solar panel 10W in artificial light 4445 lux

The I-U characteristic (4445 lux) and the technical parameters of the 10W panel (35W/m^2) are shown in Fig. 16a and Fig. 16b. The determinations of the technical parameters and the shapes of the I-U/P-U characteristics performed in natural light (75946 lux) for the 10 W solar panel are shown in Fig. 17a and Fig. 17b.

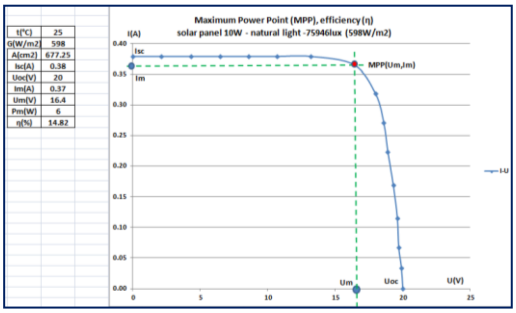


Fig. 17a. Technical parameters solar panel 10W in natural light 75946 lux (598W/m^2)

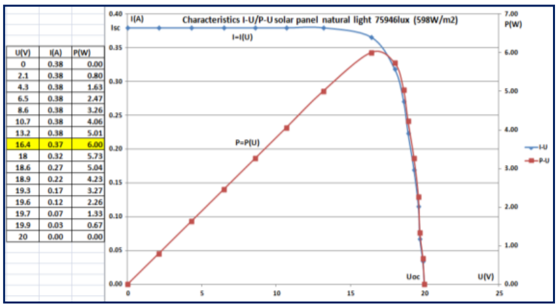


Fig. 17b. Characteristics I-U/P-U solar panel 10W in natural light 75946 lux (598W/m^2)

From the analysis of the characteristics of this 10W panel, a strong dependence of its energy efficiency on the ambient lighting level is observed. While in artificial lighting (4445lux) the maximum power point is at the value of 347.47mW, in natural light (75946lux) it rises to the value of 6W. The panel is indicated for the electrical supply, through a 12V battery, of devices that require moderate current consumption (350mA). A comparison of the I-U characteristic variations with the level irradiance is shown in Fig. 18 and of I-U / P-U in Fig. 19:

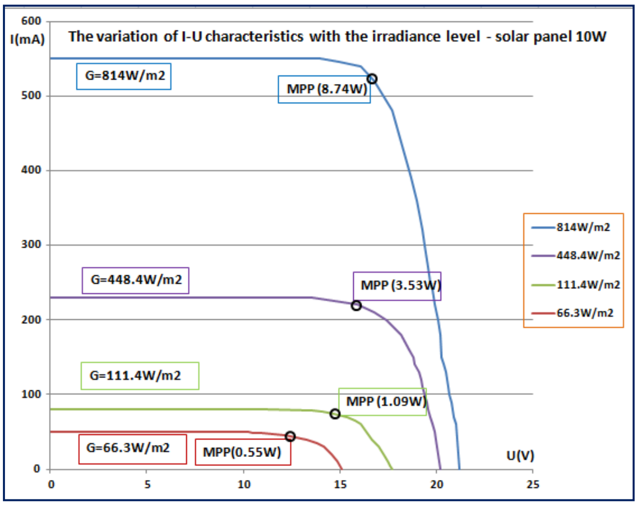


Fig. 18. I-U characteristics solar panel 10W under different irradiance levels - natural light

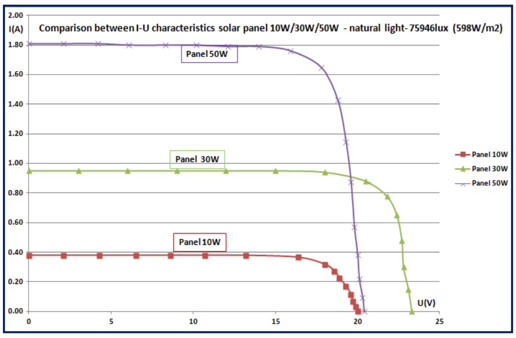


Fig. 19a. Comparison of I-U characteristics

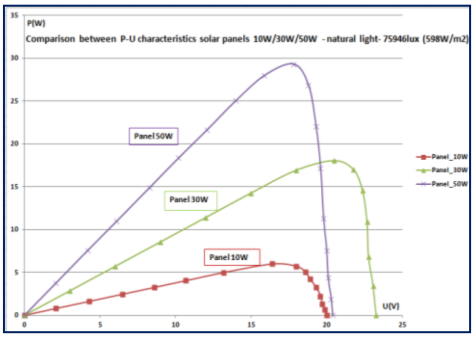


Fig. 19b. Comparison of P-U characteristics

From the analysis of the graphs in Fig. 18 an almost exponential increase of the peak power point with illumination is observed. The difference between the characteristics from Fig. 19 is determined by the type of solar cells from which the panels were made. The practical applications of this solar panels are extremely varied. The mini-panels used in the laboratory experiments were used to charge mobile phones, operate some toys based on solar energy, power mini-water pumps used to water flowerpots, provide low-power indoor lighting etc.

5. IoT monitored photovoltaic system

A solar panel works as long as it is illuminated. The decrease in the brightness of the environment causes the decrease in the efficiency of the solar panel. Even if, under cloudy sky conditions, the panel still produces electrical voltage, its energy efficiency is greatly reduced. In order to ensure continuity in the supply of some devices with electricity, it is necessary that the energy produced by a solar panel can be stored. This is precisely why a solar panel requires a voltage controller and an electric battery. Given that most household appliances operate in alternating current, an inverter module is needed. Thus, the assembly consisting of a solar panel, a voltage controller, a battery and an inverter becomes the basis of a photovoltaic system (Fig. 20a, Fig. 20b).

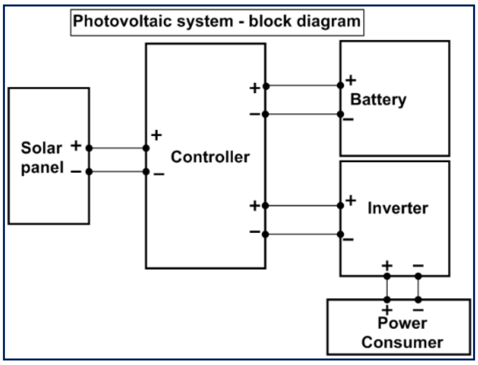


Fig. 20a. Photovoltaic system diagram

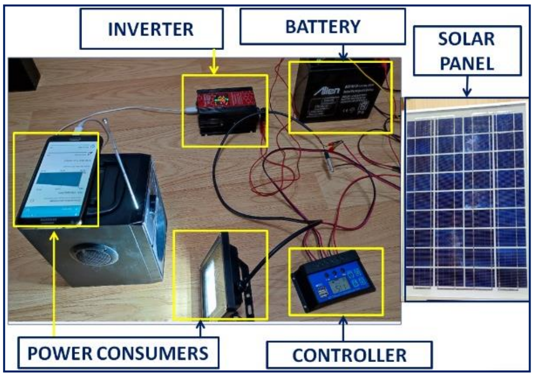


Fig. 20b. Photovoltaic system setup

An energy consumption monitoring device can also be added to this system.

The functional parameters of an autonomous photovoltaic system must be monitored. Remote access to their values can be achieved through an Internet of Things (IoT) solution. In the case of the solar panels tested in the school laboratory, we used the the NodeMCU-ESP8266 WiFi development board to transmit data on the ThingSpeak IoT platform. For starting (ON state) and stopping (OFF state) the electrical consumers in the photovoltaic system, we used a Bluetooth (BT) connection provided by the HC-05 module controlled by smartphone. Later, we extended control over ON-OFF state transitions using a web page interface. Block diagrams of these system configuration can be seen in Fig. 21.

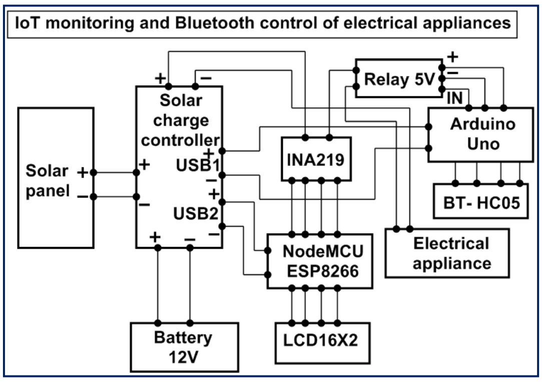


Fig. 21. IoT monitoring and BT control

The values of voltage, intensity, power and electrical energy associated with consumers within the photovoltaic system could be tracked, in real time, on the IoT ThingSpeak platform, both on mobile and fixed terminals. In this way, the following were monitored: the charging of 18650 batteries (3.7V/1200mAh) used for flashlights, the energy consumption of some LED mini panels, the consumption of some LED projectors etc. (Fig. 22).

Fig. 22. LED projector consumption monitoring on the ThingSpeak platform

We continued the functional testing of the photovoltaic system implemented at the school's Physics Laboratory using the 10W, 30W and 50W panels interconnected in series, parallel and mixed. Since we interconnected solar panels with different technical parameters, we used by-pass diodes connected in parallel with each panel. We also used anti-return diodes connected in series with the load to avoid the situation where the panels (or groups of panels) can go into power consuming mode. We connected to this photovoltaic system two indoor video surveillance cameras, four LED lighting lamps equipped with motion sensors, a wireless router, an Ethernet switch, an air quality monitoring system and a school weather station based on Arduino. We tested, separately, the operation of the system in the mode of use of some interior lighting fixtures, with LEDs.

6. Conclusions

The interdisciplinary research pursued the development of didactic procedures designed to facilitate the assimilation of some current technical concepts in the study of classical Physics. The original contribution of the work consists in the creation of a platform for monitoring and viewing the operating parameters of a large range of photovoltaic panels, adapted to the level of knowledge and understanding of the undergraduate students. Through the platform and the developed experiments, it was possible for the undergraduate students to understand the practical applicability of the theoretical concepts studied in the different Physics chapters. During the development of the project, the participating teams came up with innovative, constructive ideas and technical solutions. The students involved interacted directly with the solar cells, made a didactic solar panel and determined its functional parameters in both artificial and natural light using a device based on the INA219 current-voltage sensor, the Arduino Uno development board and the Excel Data Streamer add-in, made for real-time plotting of the panel's characteristics. They connected electrical consumers to this didactic panel and then extended the scope of the experimental investigations to low- and medium-power commercial panels. Students used different configurations of photovoltaic systems, by interconnecting the panels in series, parallel and mixed. It should also be emphasized the particularly important contribution made by the student teams participating in the project to the designing and building of the IoT monitoring device of the photovoltaic system parameters. The students understood the importance of solar energy as a non-polluting alternative energy resource, in a geographical area with a particularly high annual solarization index.

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