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**Article**

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# Techno-Economic Analysis of MPPT and PWM Controllers Performance in Off-Grid PV Systems

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**ABSTRACT**

The type of controller implemented in a photovoltaic system is of vital importance, since these devices control the energy input coming from the solar modules to regulate the batteries charge. An efficient controller makes it possible to take full advantage of the solar modules power, maximizing the energy obtained. In this paper a techno-economic analysis to measure the performance of MPPT and PWM controllers in a low power off-grid PV system is presented. To achieve this objective, the modeling of a 65 W PV system was performed, which is composed of a solar module, a DC-DC converter, a controller, and a 12 V battery. The modeling was performed in Matlab-Simulink, with which the power data and average monthly energy generated were obtained, using the city of Santa Marta Colombia as a case study. The technical results show that the MPPT controller generates a higher amount of monthly average energy (10.5 kWh) compared to the PWM controller (7.19 kWh) and the data estimated in the Global Solar Atlas (8.22 kWh). From the economic perspective, it was shown that it is possible to implement MPPT controllers in low-power PV systems, due to the energy surpluses obtained and the investment recovery time.

**Keywords:** Renewable Energy, Solar Energy, Economic Analysis of PV System Controllers
**JEL Classifications:** Q20, Q42, O13, P18

## 1. INTRODUCTION

Due to environmental problems such as pollution and global warming, as well as the rapid expansion in global energy demand, photovoltaic (PV) solar energy is presented as an attractive solution for places with high solar density (Rodríguez-Urrego and Rodríguez-Urrego, 2018). The notable increase in the use and exploitation of renewable energies as an alternative means of generating and storing clean energy is considered worldwide as one of the main technological solutions to combat climate change (Attia, 2021).

PV power is one of the fastest growing renewable technologies in large-scale commercial applications and in mini-grids of rural areas with poor access to the conventional grid (Olivero-Ortíz et al., 2021). One of the reasons for this growth is due to the decrease in the

manufacturing costs of solar panels, with values that have drastically declined in recent years. In addition, the lifespan of panels is around 30 years, which makes the investment return periods in this type of PV systems increasingly attractive (IRENA, 2022a).

According to data from the International Renewable Energy Agency (IRENA), the generation of electricity from PV systems increased by 22.85% worldwide in a period of one year, going from a production of 676,188 GWh in 2019 to 830,741 GWh in 2020. In a developing country like Colombia, electricity generation was 139.4 GWh in 2019 and 205.5 GWh in 2020, which represented an increase of 47.41% (IRENA, 2022a). In the period between 2010 and 2021 there has been a significant improvement in the competitiveness of photovoltaic systems, as the average levelized cost of electricity for large-scale PV projects decreased by 88% (IRENA, 2022b).

With this scenario of rapid growth of PV energy, research seeking to improve the efficiency of devices that make up PV systems, such as solar modules, inverters, controllers, and batteries, becomes relevant. In the case of PV installations, there are different alternatives to optimize their performance, among which solar trackers (Algarín et al., 2017), hybrid systems and maximum power point controllers (MPPT) stand out (Motahhir et al., 2020).

MPPT controllers are responsible for ensuring the highest power available to a load, regardless of variations in weather conditions. The importance of these devices has led to the development of several investigations aimed at improving the efficiency of PV systems by implementing MPPT controllers with different algorithms based on fuzzy logic, neural networks, swarm algorithms, perturb and observe algorithm (P&O), among others (Mao et al., 2020). The objective is to improve the efficiency of PV systems in operating conditions, reducing oscillations, and guaranteeing maximum power under sudden changes in irradiation, operating temperature, and effects such as partial shading in solar modules.

In general, research on this topic focuses on technical aspects whose objective is the implementation of efficient MPPT controllers in terms of maximizing output power by adjusting the duty cycle of DC-DC converters, which function as an interface between the load and solar modules (Ali et al., 2022; Leelavathi and Suresh Kumar, 2022). However, there are few works that focus on performing a techno-economic analysis that allows evaluating the advantage of implementing MPPT controllers in low power off-grid PV systems in terms of the energy surplus obtained compared to traditional PWM controllers.

For this purpose, in the present investigation a techno-economic analysis for a 65 W off-grid PV system using Matlab-Simulink was performed. This system is composed of a 65 W solar module, a Buck DC-DC converter, a 12 V battery and an MPPT controller with the P&O algorithm. For the analysis with the PWM controller, the same scheme without including the P&O algorithm was used. In that respect, this work presents as a novelty that it focuses on technical and economic aspects that allow determining the feasibility of using MPPT controllers in low-power off-grid PV systems, instead of the PWM controllers traditionally used.

This work is structured as follows: Section 2 presents the main theoretical concepts related to MPPT controllers in PV systems. Section 3 details the methodology implemented for the modeling and the proposed experiments. Finally, the results obtained with the techno-economic analysis for each of the test scenarios are presented.

## 2. MAXIMUM POWER POINT IN A PV MODULE

The maximum power output of a PV solar module can be achieved by modifying the load line. When the solar irradiation changes, the maximum power point (MPP) also changes, and it is necessary to modify the load line to continue operating the module at this point. The load connected to the module must be able to modify its impedance to achieve this goal. The Power-Voltage curve (P-V) allows understanding the operation of the PV modules (Figure 1). The MPP is the highest power that can be extracted from a module at a certain irradiation and temperature and is defined by the maximum power voltage and the maximum power current. In this figure, a region with a positive slope, a region with a negative slope, and a small region with a zero slope are identified. This fact is exploited by the controllers, which focus on finding the point of zero slope on the P-V curve, which is precisely where the MPP is located.

The output power of a PV module can be calculated by multiplying the corresponding values for voltage and current. The output power is zero when working in open circuit and short circuit; therefore, if the output of a module is short-circuited, it does not suffer any damage. To determine the MPP, the values for the standard test condition are used, which correspond to $1000 \ W/m^2$ for solar irradiation, and $25°C$ for the operating temperature.

Another important aspect in PV systems is the conversion efficiency, which is defined as the ratio between the energy generated and the light energy used to obtain it. The efficiency increases linearly with the size of the solar cell and with the level of solar irradiation and decreases linearly with the operating temperature of the cell. Currently, the most efficient solar cells are those produced at an industrial level, which have a conversion efficiency in the range of 15-22% (Zito and Pelchen, 2022). Solar cells that use monocrystalline semiconductors have a higher efficiency than those that use polycrystalline and amorphous semiconductors, because the imperfections of the latter reduce the number of free charge pairs to conduct current.

## 3. MATERIALS AND METHODS

### 3.1. Technical Modeling
To perform the techno-economic analysis of the impact of MPPT controllers in low power off-grid systems, the PV system shown in Figure 2 was implemented, which is composed of a 65 W solar module, a DC-DC converter in Buck mode, an MPPT controller

**Figure 1:** P-V curve of a 65W PV solar module
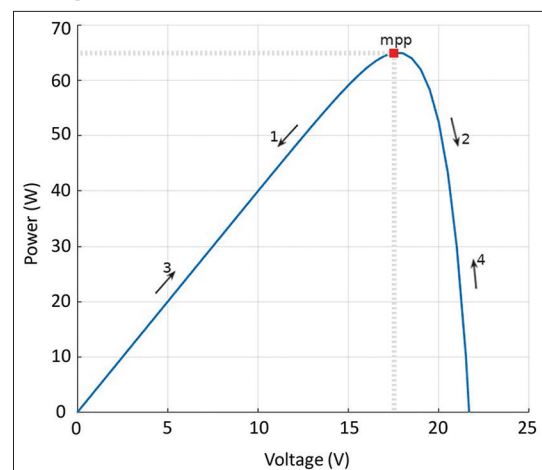
and a 12 V battery. To model the PWM controller, a system like the one presented in Figure 2 was implemented, but without the DC-DC converter and the P&O algorithm. The PWM controller was modeled as a device that matches the battery voltage (12 V) and draws current from the solar module model.

The solar module was modeled in Matlab/Simulink using equations (1), (2) and (3), which is explained in detail in previous works implemented by the authors, in MPPT controllers using intelligent control techniques (Algarín et al., 2017; Viloria-Porto et al., 2018). With these equations, the PV module can be modeled as a dynamic system for different operating conditions. $V_x$ and $I_x$ represent the open circuit voltage and short circuit current of the solar module and vary depending on the irradiation ($E_i$) and the operating temperature (T). The other variables involved in the equations are obtained directly from the datasheet of the solar module. The only parameter that must be calculated is the curve fit (b).

$$I(V) = \frac{I_x}{1 - e^{\left(\frac{-1}{b}\right)}}\left[1 - e^{\left(\frac{V}{bV_x} - \frac{1}{b}\right)}\right] \quad (1)$$

$$V_x = s\frac{E_i}{E_{iN}}TC_V\left(T - T_N\right) + sV_{max} - s\left(V_{max} - V_{min}\right)e^{\left(\frac{E_i}{E_{iN}}\ln\left|\frac{V_{max} - V_{oc}}{V_{max} - V_{min}}\right|\right)} \quad (2)$$

$$I_x = p\frac{E_i}{E_{iN}}\left[I_{sc} + TC_i\left(T - T_N\right)\right] \quad (3)$$

Figure 3 shows the PV module model, which has as inputs the solar irradiation $E_i$ in W/m² and the operating temperature T in °C. The outputs correspond to the voltage, current and power of the solar module. The parameters used for the PV module are shown in Table 1. This model was implemented using equations (1), (2) and (3), and allows evaluating the MPPT controller with the P&O algorithm and the PWM controller since delivers the output current for different operating conditions.

The DC-DC converter was implemented in Matlab/Simulink in Buck mode, with the scheme shown in Figure 4. The design process is detailed in previous research by the authors (Algarín et al., 2017), with which we obtained an inductance of L = 410 µH and capacitor of C = 280 µF. With these values the continuous conduction mode of the converter is guaranteed.

For the MPPT controller we use the P&O algorithm, due to the ease of programming and its low computational cost, which makes it ideal for implementations in low-cost microcontrollers. This way, MPPT controllers can be developed that can be price competitive with respect to PWM controllers. Figure 5 shows the flow diagram of the P&O algorithm that was developed in Matlab, whose function is to adjust the duty cycle of the DC-DC converter.

### 3.2. Case Study in Santa Marta, Colombia
To estimate the monthly energy generated by each controller independently, MPPT and PWM, we use the city of Santa Marta,



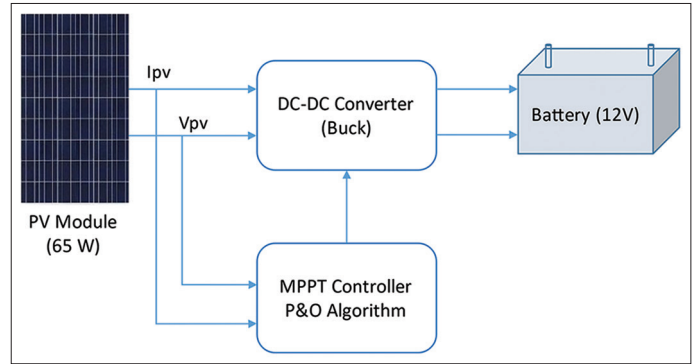**Figure 2:** PV system implemented to evaluate the MPPT controller



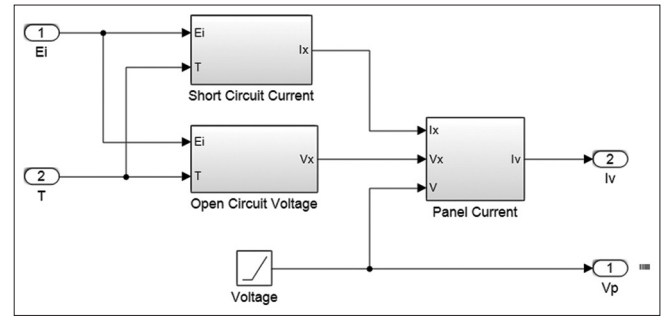**Figure 3:** Modeling in Matlab/Simulink of the 65W Solar Module

**Table 1: Parameters used for modeling the 65W PV Module (YL65P-17b)**

| Parameter | Variable | Value | Units |
|---|---|---|---|
| Open-Circuit Voltage | $V_{oc}$ | 21.70 | V |
| Short-Circuit Current | $I_{sc}$ | 4 | A |
| Voltage at Maximum Power Point | $V_{pmax}$ | 17.50 | V |
| Current at Maximum Power Point | $I_{pmax}$ | 3.71 | A |
| Maximum Voltage | $V_{max}$ | 22.351 | V |
| Minimum Voltage | $V_{min}$ | 18.445 | V |
| Temperature Coefficient of Voltage | $TC_v$ | −0.08029 | V/°C |
| Temperature Coefficient of Current | $TC_i$ | 0.0024 | A/°C |
| Curve Fit | b | 0.073756 | |

Colombia as a case study. The data corresponding to the peak sun hours reported in the Solar Atlas of Colombia were used (IDEAM, 2022). In the case of the city of Santa Marta, these data are acquired from the meteorological station installed at the Universidad del Magdalena, 11.225146183705613, -74.1855293513457.

In addition, to make comparisons, the peak sun hour data of the city of Santa Marta reported in the Global Solar Atlas were used, which have the advantage of incorporating variables such as the terrain elevation, the optimal tilt of PV modules, temperature, among others (Global Solar Atlas, 2022). Table 2 shows the monthly information reported by the Santa Marta weather station in the Solar Atlas of Colombia and the information from the Global Solar Atlas.

Finally, the estimated output power data for the city of Santa Marta, reported in the Global Solar Atlas for a 65 W PV system, were used as a reference to compare the results obtained with the MPPT and PWM controllers evaluated in this research.

**Figure 4:** Modeling in Matlab/Simulink of the DC-DC converter
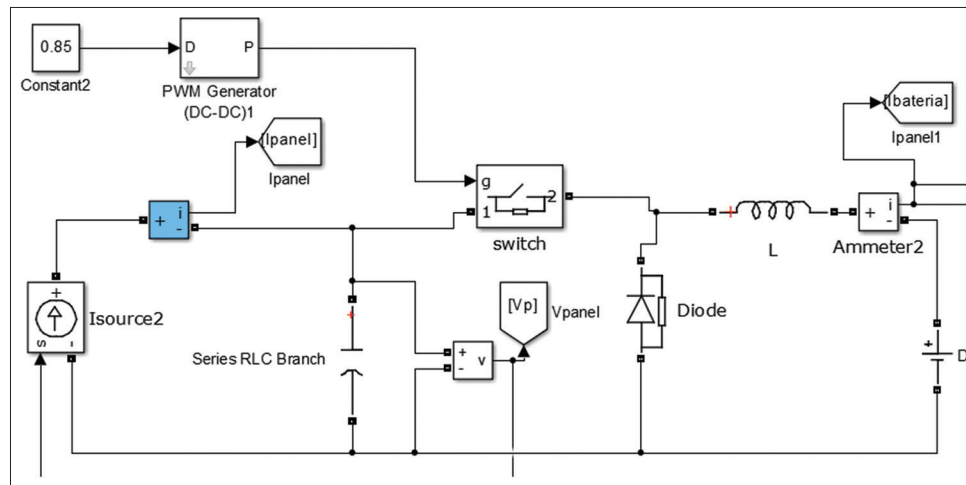


**Figure 5:** Flowchart of the P&O algorithm implemented for the MPPT controller
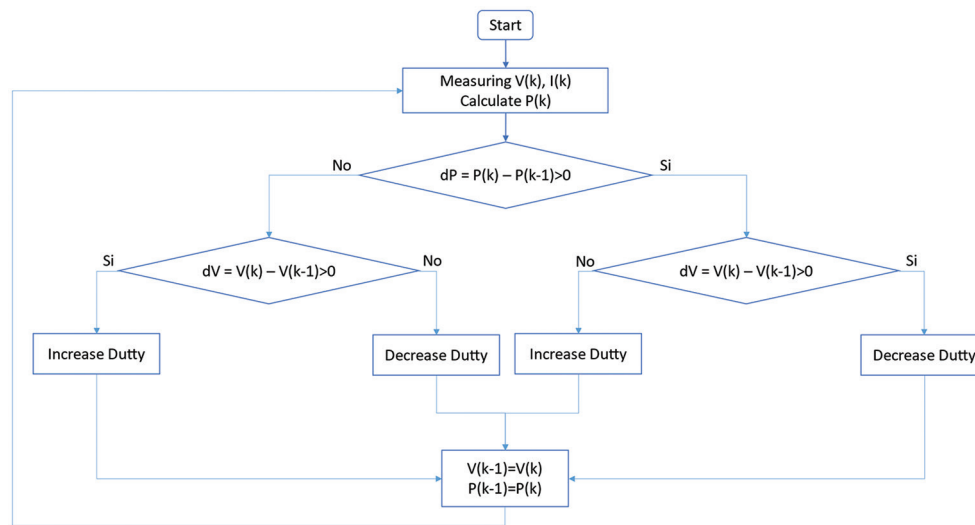


**Table 2: Monthly average of peak sun hours in the city of Santa Marta, Colombia**

|  | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Monthly Average Peak Sun Hour (Solar Atlas of Colombia) | 5.55 | 5.91 | 5.86 | 5.76 | 5.70 | 5.40 | 5.37 | 5.20 | 5.33 | 4.73 | 4.80 | 5.30 |
| Monthly Average Peak Sun Hour (Global Solar Atlas) | 5.25 | 5.41 | 5.20 | 4.64 | 4.10 | 3.97 | 4.08 | 4.13 | 4.18 | 4.11 | 4.26 | 4.77 |

# 4. RESULTS

## 4.1. Power Obtained with the Modeling of the PV System

To evaluate the performance of MPPT and PWM controllers, different experiments for variable irradiation between 100 and 1000 W/m$^2$ and operating temperature of the PV module between 25°C and 55°C were performed. In each of the scenarios, the theoretical power was calculated, which corresponds to the maximum power that the 65 W PV module can deliver for the defined irradiation and temperature conditions. The theoretical power was obtained from the mathematical modeling of the PV module in Matlab.

With the modeling of the controllers, the average power data for the MPPT and the PWM were obtained, using the same operating conditions defined for the calculation of the theoretical power. Finally, the calculation of the efficiency for the two controllers was performed, which was measured in terms of the maximum theoretical power that should be produced in the 65 W PV system. Tables 3-6 show the results obtained.

Table 3 shows the results for a temperature of 25°C, in which the MPPT controller is very efficient for all irradiation values evaluated, with data ranging between 97.74% and 99.56%, in contrast with the PWM controller having efficiencies between 68.20% and 75.31%. It is worth highlighting the high efficiency of the MPPT controller for standard test conditions (T=25°C and E$_i$=1000 W/m$^2$), in which a power of 64.70 W was obtained, which is approximately equal to the theoretical value of 64.98 W.

**Table 3: Power results for variable irradiation and temperature of 25°C**

| Irradiation (W/m²) | Theoretical power (W) | Power with MPPT P&O (W) | Power with PWM (W) | Efficiency MPPT (%) | Efficiency PWM (%) |
|---|---|---|---|---|---|
| 100 | 5.72 | 5.59 | 4.30 | 97.74 | 75.31 |
| 200 | 11.75 | 11.55 | 8.72 | 98.30 | 74.20 |
| 300 | 18.03 | 17.75 | 13.16 | 98.47 | 73.02 |
| 400 | 24.49 | 24.04 | 17.62 | 98.18 | 71.94 |
| 500 | 31.08 | 30.60 | 22.06 | 98.47 | 70.99 |
| 600 | 37.76 | 37.05 | 26.52 | 98.11 | 70.23 |
| 700 | 44.50 | 43.73 | 30.96 | 98.27 | 69.58 |
| 800 | 51.31 | 50.45 | 35.41 | 98.32 | 69.01 |
| 900 | 58.13 | 59.94 | 39.86 | 99.77 | 68.57 |
| 1000 | 64.98 | 64.70 | 44.32 | 99.56 | 68.20 |

**Table 4: Power results for variable irradiation and temperature of 35°C**

| Irradiation (W/m²) | Theoretical power (W) | Power with MPPT P&O (W) | Power with PWM (W) | Efficiency MPPT (%) | Efficiency PWM (%) |
|---|---|---|---|---|---|
| 100 | 5.73 | 5.58 | 4.32 | 97.43 | 75.41 |
| 200 | 11.72 | 11.50 | 8.75 | 98.14 | 74.63 |
| 300 | 17.92 | 17.57 | 13.21 | 98.04 | 73.70 |
| 400 | 24.25 | 23.88 | 17.68 | 98.48 | 72.90 |
| 500 | 30.65 | 30.08 | 22.17 | 98.14 | 72.32 |
| 600 | 37.12 | 36.49 | 26.63 | 98.31 | 71.75 |
| 700 | 43.59 | 42.89 | 31.09 | 98.39 | 71.33 |
| 800 | 50.07 | 49.28 | 35.57 | 98.42 | 71.04 |
| 900 | 56.53 | 55.49 | 40.02 | 98.17 | 70.80 |
| 1000 | 62.94 | 61.77 | 44.52 | 98.13 | 70.73 |

**Table 5: Power results for variable irradiation and temperature of 45°C**

| Irradiation (W/m²) | Theoretical power (W) | Power with MPPT P&O (W) | Power with PWM (W) | Efficiency MPPT (%) | Efficiency PWM (%) |
|---|---|---|---|---|---|
| 100 | 5.74 | 5.58 | 4.33 | 97.28 | 75.53 |
| 200 | 11.70 | 11.42 | 8.77 | 97.64 | 74.99 |
| 300 | 17.81 | 17.51 | 13.24 | 98.34 | 74.33 |
| 400 | 24.00 | 23.54 | 17.73 | 98.07 | 73.86 |
| 500 | 30.23 | 29.71 | 22.21 | 98.27 | 73.47 |
| 600 | 36.46 | 35.87 | 26.69 | 98.40 | 73.21 |
| 700 | 42.66 | 41.99 | 31.16 | 98.42 | 73.04 |
| 800 | 48.81 | 48.04 | 35.61 | 98.41 | 72.96 |
| 900 | 54.89 | 54.01 | 40.08 | 98.39 | 73.02 |
| 1000 | 60.89 | 59.90 | 44.53 | 98.38 | 73.14 |

In the other simulation scenarios, represented in Tables 4-6, a behavior like that shown in Table 3 is observed. That is, high efficiency values are observed with the MPPT controller compared to the PWM controller, independently of the increases in the operating temperature of the PV module. It should be noted that the values used for irradiation and operating temperature correspond to those presented in the study area of this investigation.

## 4.2. Techno-Economic Analysis of the Energy Generated

With the monthly average peak sun hours for the city of Santa Marta obtained from the Solar Atlas of Colombia (Table 2) and the power data obtained in the previous section, we perform an analysis of the average monthly energy (kWh) that can be obtained with each of the controllers, MPPT and PWM. We use the power data obtained in Table 3 for standard test conditions (T=25 °C and irradiation 1000 W/m²), since this scenario represents the case where the maximum power of the PV module is obtained (65 W).

The results are shown in Table 7, in which the monthly average energy was obtained according to equation (4).

$$Energy\,(kWh) = \frac{PSH \times 30 \times Power\,(W)}{1000} \tag{4}$$

The values obtained show that with the MPPT controller, a greater amount of monthly average energy is obtained. The surpluses have a minimum value of 2.9 kWh and a maximum of 3.6 kWh, but in general, 46% more energy is obtained with the MPPT controller compared to the PWM. By averaging the monthly energy obtained with the MPPT controller, a value of 10.5 kWh is obtained, compared to 7.2 kWh of the PWM. According to data from the Mining and Energy Planning Unit (UPME), the average consumption of a Colombian home is 157 kWh per month, therefore with a PV system with a basic MPPT controller (UPME, 2019), such as the one modeled in this research, it is possible to supply 6.7% of the consumption of this type of housing.

**Table 6: Power results for variable irradiation and temperature of 55°C**

| Irradiation (W/m²) | Theoretical power (W) | Power with MPPT P&O (W) | Power with PWM (W) | Efficiency MPPT (%) | Efficiency PWM (%) |
|---|---|---|---|---|---|
| 100 | 5.74 | 5.57 | 4.35 | 96.99 | 75.72 |
| 200 | 11.67 | 11.31 | 8.80 | 96.93 | 75.40 |
| 300 | 17.69 | 17.32 | 13.26 | 97.87 | 74.93 |
| 400 | 23.75 | 23.31 | 17.73 | 98.14 | 74.66 |
| 500 | 29.80 | 29.27 | 22.20 | 98.23 | 74.50 |
| 600 | 35.80 | 35.18 | 26.67 | 98.26 | 74.50 |
| 700 | 41.72 | 40.97 | 31.11 | 98.21 | 74.58 |
| 800 | 47.53 | 46.65 | 35.54 | 98.16 | 74.77 |
| 900 | 53.23 | 52.20 | 39.91 | 98.07 | 74.98 |
| 1000 | 58.81 | 57.57 | 44.25 | 97.89 | 75.24 |

**Table 7: Monthly average energy generated with the controllers**

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Peak Sun Hour | 5.5 | 5.9 | 5.9 | 5.8 | 5.7 | 5.4 | 5.4 | 5.2 | 5.3 | 4.7 | 4.8 | 5.3 |
| Monthly Average Energy MPPT (kWh) | 10.8 | 11.5 | 11.4 | 11.2 | 11.1 | 10.5 | 10.4 | 10.1 | 10.3 | 9.2 | 9.3 | 10.3 |
| Monthly Average Energy PWM (kWh) | 7.4 | 7.9 | 7.8 | 7.7 | 7.6 | 7.2 | 7.1 | 6.9 | 7.1 | 6.3 | 6.4 | 7.0 |
| Difference MPPT Vs PWM (kWh) | 3.4 | 3.6 | 3.6 | 3.5 | 3.5 | 3.3 | 3.3 | 3.2 | 3.3 | 2.9 | 2.9 | 3.2 |
| Surplus Energy with MPPT | 46% | 46% | 46% | 46% | 46% | 46% | 46% | 46% | 46% | 46% | 46% | 46% |

**Table 8: Cost analysis for investment recovery using MPPT controller**

| Annual MPPT Energy (kWh) | Annual PWM Energy (kWh) | Surplus Energy with MPPT (kWh) | Cost of Surplus Energy (USD) | Investment Recovery (Years) |
|---|---|---|---|---|
| 125.97 | 86.28 | 39.69 | 7.09 | 3.02 |

**Figure 6:** Comparison of the average monthly energy obtained for the 65 W PV system
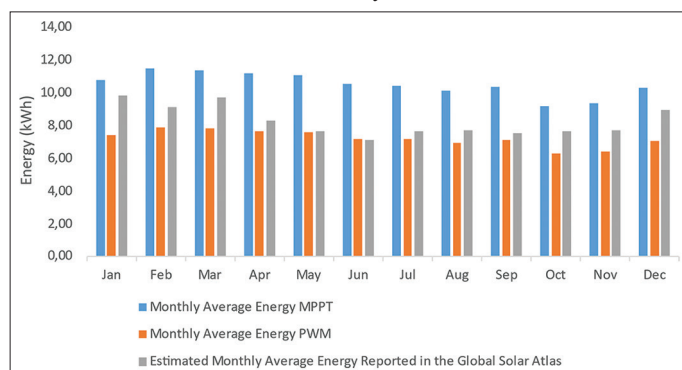


The monthly average energy results were also compared with the data reported in the Global Solar Atlas for the city of Santa Marta. Figure 6 shows the comparisons made for the 65 W PV system. The system with the MPPT controller generates higher monthly average energy, with an annual production of 125.97 kWh, compared to 86.28 kWh for the PWM and the 98.6 kWh estimated in the Global Solar Atlas. As expected, the estimated results in the Global Atlas are lower than the energy obtained with the MPPT, since the calculations are made with the peak sun hours shown in Table 2, whose values are lower than those reported in the Solar Atlas of Colombia.

Otherwise, from the economic perspective, the price difference between MPPT and PWM controllers of 10A in the Colombian market for some references is approximately $22 USD, which generates the possibility of implementing MPPT controllers in off-grid PV systems, considering that the additional investment for the acquisition of MPPT controller is recovered with the surplus energy obtained (Table 8).

For the calculations presented in Table 8, an average cost of $12 USD was used for the PWM controller and $33.5 USD for the MPPT (10A Controllers). In addition, the investment recovery was calculated simple without considering the time value of money and using the price difference between the controllers as a base. Also, we use an average value of 0.18 USD for the kWh, which corresponds to the estimated cost for the City of Santa Marta, Colombia.

## 5. CONCLUSIONS

At the end of this work, it can be concluded that the results obtained with the modeling show that it is profitable to implement MPPT controllers in low-power off-grid PV systems, since the energy surpluses obtained compared to the traditionally used PWM controller compensate the additional costs of MPPT controllers in a period of approximately 3 years. It is highlighted that this research focused on off-grid low-power PV systems, since PWM controllers are extensively used in these systems.

With the MPPT controller, an annual average energy surplus of 39.69 kWh was obtained with respect to the PWM controller and 27.37 kWh in relation to the data estimated in the Global Solar Atlas for a 65 W off-grid PV system. This way, it was possible to demonstrate that an MPPT controller programmed with an easy-to-implement algorithm such as Perturb and Observe (P&O), is presented as an excellent alternative for low-power PV systems

to replace traditionally implemented PWM controllers. As future work, other intelligent control algorithms can be evaluated and a detailed economic analysis can be performed regarding the implementation costs of MPPT controllers for low-power systems, since these types of controllers are commercially available for higher-power systems.

## 6. ACKNOWLEDGMENTS

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