

Design and Construction of a Stand-Alone PV System for Charging Mobile Devices in Urban Landscapes in Medellin

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Abstract- Stand-Alone PV System (SAPVS) supplies an alternative means of electrification in urban landscapes that are not connected to power utility grids and that have a high flow of visitors. People are constantly using their mobile devices and in open spaces, it is difficult to get access to battery charging stations. This paper shows the design and construction of an SAPVS for charging mobile devices in urban landscapes in Medellín, based on mobile device consumption and portable equipment calculations and technical variables such as intensity of solar radiation, capacity of panels and batteries. SAPVS use solar photovoltaic power as a renewable energy source; it has 6 photovoltaic solar panels with flexible technology that allows to supply the energy of the lighting system, the control system and the charging system. It has a storage capacity of 240Ah, with 4 USB ports for connecting mobile devices and 2 110V - 1000W power sockets for connecting laptops. Based on different operation tests, it has been verified that the photovoltaic solar system was able to satisfy the energy requirements, obtaining an autonomy of the system in saturation of 7 hours and an energy saving of 1246Wh, equivalent to a consumption of 230.180W; generating thus savings of 89,758.69 gr of CO₂ emissions in one year of operation. This option has shown that SAPVS can adequately meet the people's energy needs and contribute to improve the landscape and Medellín's environment.

Keywords Stand-alone PV system, photovoltaic solar system, renewable energy sources, Battery charging station, flexible solar panel.

1. Introduction

Today, the issue of renewable energies has become more important because of the problems caused by fossil fuels, such as limited reserves, volatility in oil prices, problems associated with pollution and global warming. One of the most promising sources of renewable energy today is solar energy because it is clean, renewable, safe and abundant [1] [2]; it is obtained

from the use of electromagnetic radiation emitted by the sun through sensors. Thermal collectors or photovoltaic cells, are able to transform such radiation into electrical or thermal energy. Solar energy has a significant role in meeting the increased requirements of electricity reducing the environmental impact [3], [4].

There has been an enormous effort from the scientific community to look for alternative and clean energy resources

to fulfill the present and future needs. Also, due to the limitation of conventional energy resources, there is an urgent need to explore renewable energy resources for healthy, competitive and sustainable economic growth worldwide, while keeping the environment neat and clean for the coming generations. The collection of environmentally friendly energy, in particular solar based, has emerged as a viable technique to complement battery supplies [5]. The recent advances of PV technologies have closed certain gaps between power demand and supply through a wide range of new emerging applications in general, and in some areas with technical difficulties in particular [6]. Currently, the world energy consumption is 10 terawatts (TW) per year and by 2050, it is projected to be about 30 TW. The world will need about 20 TW of non-CO₂ energy to stabilize CO₂ in the atmosphere by mid -century [7].

Photovoltaic energy has become increasingly important as a renewable source because it is environmentally friendly, non-polluting, not noisy, free and it requires little maintenance compared to other resources and it is easy to expand. Consequently, these advantages make PV generation attractive for many applications, especially in rural and remote areas in most of the developing countries [8].

Electricity is one of the basic needs of the modern population and constitutes an essential indicator for economic growth and social welfare [9] - [11]. Access to electricity continues to be one of the public policies at to achieve economic, social, political and regional development goals. More than 1.3 billion people in the world have access to electricity, and over 84% of them live in rural areas in the developing countries [12]. According to [13], electricity access has a positive correlation with the human development index (HDI) and electricity consumption per capita represents critical access to human development in emerging countries.

Electric energy has many uses and many of them contribute to the well-being of people. Today, people consume one or two hours a day to charge their mobile devices and sometimes, they do not have available power or charging points to do so, especially in open spaces. The need to be constantly informed and connected with other people has made cellphones and tablets a fundamental part of daily lives of men and women in the world. According to the report presented by Colombia's ICT Department, by the end of 2015, the total number of mobile phone subscribers in Colombia was 53,583,664, while the number of inhabitants does not exceed 48 million. Also, according to the "Industry Report 2014" (carried out by the Colombian Commission on Communications Regulation), [14] mobile connections are growing fast in Colombia with 58% in 2015. For this reason, this work evaluates the configuration of a solar table for charging mobile devices for urban areas in the city of Medellín, Colombia; this is for offering available points of electrical connection so that passers-by can freely access electricity and remain connected. This paper is focused on a stand-alone hybrid system with only PV panels as primary energy source.

The article has been structured as follows: Chapter 2 addresses the basic concepts of photovoltaic systems, presenting their operation and main advances in the world. In the third chapter, the design of the stand-alone PV system and its consumption calculations is presented. Chapter 4 presents a proposal for the implementation of such a system for use in urban landscapes in the city of Medellín, and reviews the economic and environmental benefits of the project. Finally, Section 5 establishes the conclusions.

2. Solar Energy and Photovoltaic (PV) System

The solar photovoltaic system has played a very important and critical role in the electrification of rural areas particularly in the developing world [6]. Fig. 1 shows the configuration of the stand-alone solar PV system proposed in this work, which consists of five main elements including a photovoltaic array (solar modules), a solar charge controller, a batteries bank, a power inverter and electronic circuits.

A photovoltaic cell is a non-mechanical device usually made from silicon alloys. Sunlight is composed of photons or solar energy particles. These photons contain various amounts of energy corresponding to the different wavelengths within the solar spectrum. When a photon strikes a photovoltaic cell, it may be reflected, pass right through, or be absorbed depending on the amount of energy it contains. Only the absorbed photons provide energy to generate electricity [15].

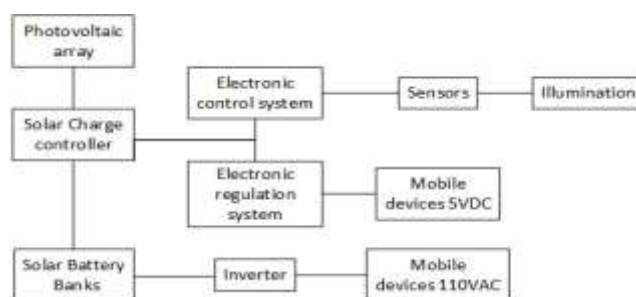


Fig 1. Configuration of the Stand-alone PV system under study

2.1. The Photovoltaic Cell

The following factors are usually considered when determining the performance of a photovoltaic solar panel: characterization of solar cells performance, determination of degradation factors related to the design and mounting of the photovoltaic panel, consideration of the environmental conditions and their effects on the operating temperature of the solar cells and calculation of the output power of the solar panel.

A solar PV cell is a P-N junction semiconductor device which generates electric current when photons of energy higher than the energy band gap of semiconducting materials falls on it. These cells are arranged into series and parallel combinations to form a PV module [16]

Different types of PV materials for solar cells are available in the market nowadays [6]. Crystalline

semiconductors viz. Si and GaAs have the highest performance as compared to the other options available in the market. While, the solar cells based on the less pure materials viz. polycrystalline or amorphous inorganic or organic materials, or a combination of these have less performance but their cost is lower [17].

2.2. Solar Charge Controller

Voltage and frequency change when there are alterations in the energy demand [16]. The basic function of this device is to prevent discharges and overloads in the battery. It is also used to protect loads under extreme operating conditions and provide information to the user. The charge regulation function should ideally depend directly on the state of charge in the battery. A charge controller regulates power from a PV module to prevent batteries from overcharging and unacceptable voltage levels; it also functions as a low-voltage disconnect switch to cut off DC charge from the battery, preventing them from over-discharge [18], [19].

2.3. Batteries Bank

In order to have available energy in the absence of solar radiation, a relative balance among the solar cells is required; they are the heart of the system and constitute the energy storage system. In this situation, a battery system is needed for the storage of energy supplied by the photovoltaic system. The most commonly used energy storage devices are the VRLA (Valve Regulated Lead Acid) [20]. In order for a battery to be used in a stand-alone solar PV system, it has to be charged during sun hours and it has to withstand deep discharge during sunless hours; the batteries are called deep cycle batteries.

2.4. Invert

Due to the fact that photovoltaic panels only supply continuous or unidirectional current when illuminated by sunlight, it is required to convert this continuous electric current into alternating current. To do this, an inverter is used; it acts as a coupling element between the continuous electricity generated by the photovoltaic solar panel and the charge that requires alternating current. Its function is to adapt the characteristics of the energy generated to the demanded through the applications of the system. Some of the main features an inverter must have are: power or input voltage, maximum output power and efficiency.

3. Methodology

Dimensioning a photovoltaic system aims at calculating the elements of the system in order to be able to safely determine the electrical consumption and to be able to satisfy it. The methodology presented in this paper shows several activities that can be arranged as follows:

3.1. Calculation of Solar Radiation

Options such as wind and solar energy will play an important role in the long term and will produce substantial changes in Colombia's energy matrix. Solar energy plays a significant role in the current context of increased requirements of power with a reduced environmental impact

[4]. In addition, solar energy systems are being pursued by many countries, which have a monthly 3-6 kWh / m² average of solar radiation levels [2]. According to NASA's Atmospheric Science Data Center, the monthly averaged insolation clearness index and radiation incident on an Equator-pointed tilted for a site in Medellín, Colombia (6.217 Latitude / -75.567 Longitude) are summarized in figure 2.

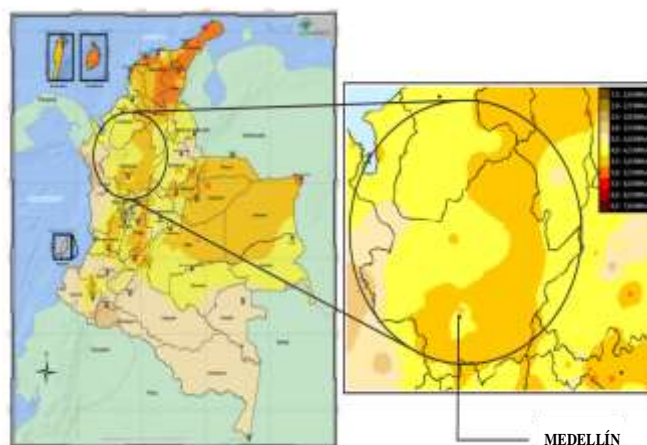


Fig. 2. Colombian Solar Map

For the case of Colombia, available sources of solar resource information indicate that the country has an average irradiance of 4.5 kWh / m² / d [21], which exceeds the world average of 3.9 kWh / m² / D.

3.2. Consumption Estimation

To design the photovoltaic solar energy system, we need to know the total power of the loads to be connected to the system and thus, determine the daily energy that will be needed for the station.

The calculation of the theoretical energy required per day is estimated by:

$$E_T = \sum_i^n W_i * h \quad (1)$$

Where:

E_T= Required theoretical energy (Wh)

W_i= The equipment's rated power i (W)

h= Daily usage time (h)

Table 1 shows detailed consumption calculations. This operation was performed based on the power summation, considering the number of devices of each type and their operating hours.

Table 1. Consumption calculations Stand-alone PV system at full charge

DESCRIPTION	QUANTITY	POWER	DAILY USE HOURS	TOTAL
CELPHONE (10W)	4	10W	7	280Wh
LAPTOP (65W)	2	65W	7	910Wh
LIGHTING (2W)	1	2W	7	56Wh
			E_T	1246Wh

From this value, the actual energy consumption must be calculated; it considers the various loss factors in the photovoltaic system according to the following equation:

$$E_R = \frac{E_T}{R} = \frac{1246Wh}{0,809} = 1540Wh \quad (2)$$

Where:

E_R = Real energy (Wh)

R= Global performance of the photovoltaic system; it is calculated through the following equation:

$$R = 1 - [(1 - kb - kc - kv) * ka * \frac{N}{PD}] = 0.809 \quad (3)$$

Where:

- Ka = Auto-discharge coefficient
- Kb =Performance loss coefficient
- Kc = Inverter loss coefficient
- Kv = Other loss coefficient
- PD = Discharge depth
- N = the system's autonomy in days

3.3. To Determine the Batteries Bank

To determine the size of the storage system, it is necessary to estimate the number of days that the system is be able to operate when there is no sunlight and the maximum discharge rate that the battery can reach. For this, equation 4 is used.

$$C_B = \frac{E_R * N}{V * D_d} = 233 Ah \quad (4)$$

Where:

- CB =The system's batteries capacity (Ah)
- ER = Real power (W)
- V =The panel's voltage (V)
- Dd = Depth per discharge (%)
- N = The system's autonomy in days (day)

Finally, after determining the battery's capacity, the number of batteries that will be connected in parallel is defined, so as to have a bank of batteries, so that it is possible to back up the system with the required days of autonomy. The number of batteries required is determined by:

$$N_{bat} = \frac{C_B}{C_F} = 2 \quad (5)$$

Where:

- Nbat =The number of required batteries by the system
- CB =The system's batteries capacity (Ah)
- CF =The batteries' capacity given by their manufacturer (Ah)

The capacity of each battery is 120 Ah and 2 batteries are required for the system, for a total of 240 Ah. The batteries selected for the development of the project are AGM VRLA type.

3.4. Determining the Size of the Photovoltaic System

Designing the photovoltaic system considered energy losses of 10%, so a higher energy generation than the calculated consumption is available. In addition, it was taken into account that solar irradiation for Colombia is between 4 to 6 hours a day. In order to calculate the number of panels required, a 4-hour solar radiation peak was established. The following equation represents the calculations:

$$N_p = \frac{E_R}{P_p * P_{max} * h_{ps}} = 6 \quad (6)$$

Where:

- N_p =The number of required panels for the system
- E_R = Real power (Wh)
- P_p =The solar panel's loss percentage (%)
- P_{max} = The solar panel's peak power (W)
- H_{ps} = The number of radiation peak hours in a day (h)

The system uses 6 flexible solar panels connected in parallel, each one is 72 Watts, in order to guarantee the total power required for the system. These panels are located on top of the stand-alone PV system.

3.5. Estimation of the Solar Charge Controller

According to the regulator's dimensions, the project intends to obtain the maximum current that will circulate through the photovoltaic station in a safe way. The following equation represents the calculation of the regulator's capacity:

$$I_{max} = I_{sc} * N_p = 32A \quad (7)$$

Where:

- I_{max} =The system’s maximum current (A)
- I_{sc} = The short circuit current’s intensity in the solar panel (A)
- N_p =The number of solar panels

Taking into account that, commercially the regulators do not have this capacity, it was determined to use a 35 Amperes regulator.

3.6. Determining the Inverter’s Size

The inverter will be defined taking into account the power demanded by the system as AC, as shown below:

$$P_{inv} = P_{AC} = 130 W \tag{8}$$

Where:

- P_{inv} =The inverter’s power (W)
- P_{ac} = The AC power demanded by the charge (W)

The requested power by the charge in alternating current corresponds to the use of 2 portable equipment of 65W each approximately; this is why the power of the required inverter is of 130 W. A commercial inverter with a power of 1000 W is selected in order to support connections of devices requiring more power, this as an additional function, and in case of requesting it, the discharge of the batteries will be in less time than calculated.

3.7. Calculating the Required Wiring

In order to calculate the required wiring, it is important to consider the length of the cables (in order to avoid losses caused by the Joule Effect) so the shortest possible lengths, voltage drops and wiring resistance are minimum. Equation 9 represents the relations between the section and the length of the cable.

$$S = \frac{p \cdot L}{R_{ps}} = 1.628 mm^2 \tag{9}$$

Where:

- S= The conductor’s section (mm2)
- L= The conductor’s length (m)
- p= The conductor’s resistance ($\Omega \cdot mm^2/m$)
- Rps= The photovoltaic system’s resistance (Ω)

In order to develop this project, an AWG14 copper wire with a 1.628 mm2 section has been considered.

3.8. Designing the Control System

The Stand-alone PV system has lighting in the working area. It lights up in the night hours when the presence of people is detected. For this, an automatic lighting control system was designed by means of proximity sensors and photoelectric sensors; they detect the presence of the system’s users and the

absence of light intensity in the environment, respectively. This design is divided into three stages:

Stage one. The absence of sunlight is detected by means of a LDR sensor (as its main component) and an operational amplifier configured as a voltage comparator. The two signals are evaluated, one is supplied by voltage dividers and the other by the LDR sensor. In the case of the sensor, when there is incident light, it produces a low signal and when there is no incidence of light, it produces a high signal; it causes a determined output signal in the circuit as "LDR Output" to then be coupled and Processed by a 16F628A PIC microcontroller.

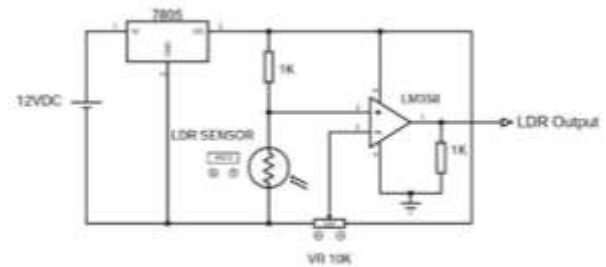


Fig. 3. Photoelectric Sensor Controller Schematic.

Stage Two. The optical sensors are connected. This allows the identification of the presence of persons in the stand-alone PV system and send a signal to the microcontroller.

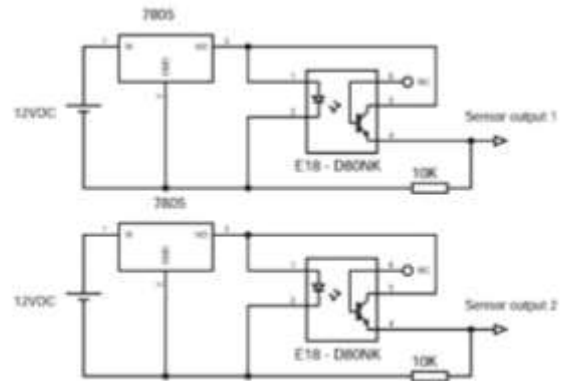


Fig. 4. E18 - 80NK Optical Sensor Connection Schematic

Stage three. The signal from the LDR and from the optical sensors are taken into the 16F628A PIC microcontroller. There, an algorithm is created, and by means of it, it is decided to turn on the light of the stand-alone PV system if case of daylight absence or in case of an interruption of the optical sensor signal caused by the presence of persons.

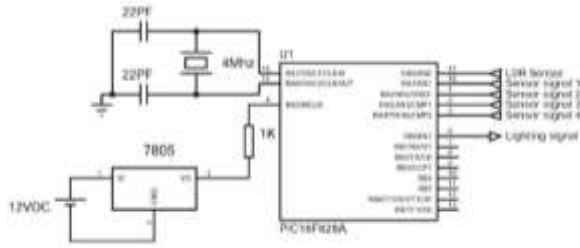


Fig. 5 Stand-alone PV system’s Lighting Controller Connection Schematic

3.9. Designing the Battery’s Status Indicator

In order to avoid that the storage system reaches the minimum discharge percentage, a battery status indicator card was implemented. It allows to visually know the charge level (thanks to indicating LEDs).

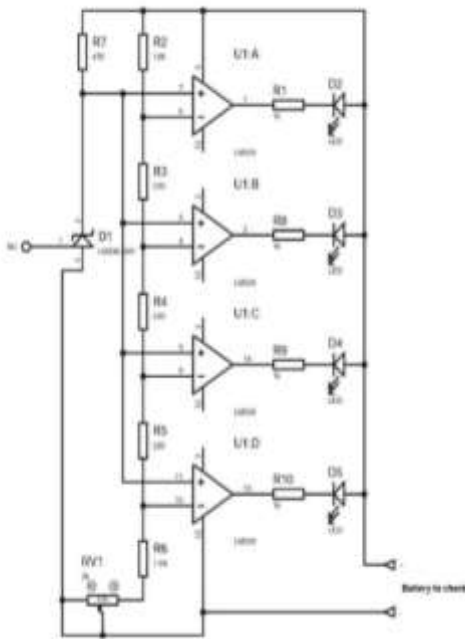


Fig. 6 Connecting the Battery’s Charging Indication System Schematic.

3.10. Designing the Stand-alone PV System

Based on the calculations previously presented, the Stand-alone PV System was designed in Solid Edge ST9, SOLIDWORKS 2017, Luxion KeyShot 6, CorelDRAW X8, and Microsoft Visio 2016 to simulate the shape and location of each component and the choice of the building material.

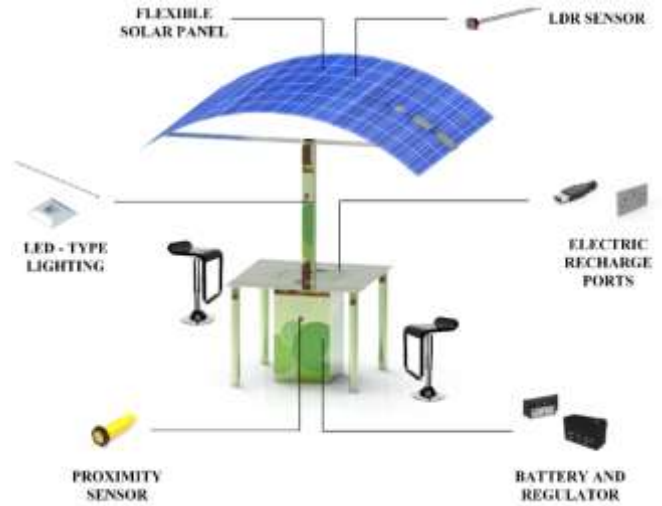


Fig. 7. Design Proposal of the Stand-alone PV System

4. Results and Discussion

4.1. Construction of Stand-alone PV System

After having clear design parameters, we proceeded to the construction of the Stand-alone PV System.

The Stand-alone PV System has a white LED light that illuminates the working area; its roof allows the placement of flexible-technology solar panels. The System also has four stainless steel seats.



Fig. 8. Actual Image of the Stand-alone PV System

Source: The Stand-alone PV System Prototype pictured at Pascual Bravo University

The prototype has the following technical features:

- Operating Voltage: 12VDC
- Storage capacity: 240Ah (two 120Ah batteries)
- Power Inverter: 1000W

- Charge Controller: 35A
- Use Capacity: 4 USB ports for connecting mobile devices, 2 sockets for connecting portable equipment (110V - 1000W)
- Autonomy of the system in saturation: 7 hours
- Battery discharge indicator (Green 100%, Yellow 75%, Yellow 50%, Red 25%)

The Stand-alone PV System prototype was installed at Pascual Bravo University in Medellin – Colombia. Different tests were carried out in 2016. They included energy consumption per charge of mobile devices, number of users benefited, energy saving and CO2 reduction in the atmosphere.

To validate the prototype’s power generation results, an electronic energy meter was installed in DC current with a nominal voltage range of 5 to 800VDC reference MK-DC / MK-SH-DC. This allowed to determine the energy consumption of the equipment connected to the solar energy system. From monthly data, the Stand-alone PV System showed a consumption of 230.180W and a reduction of 89,758.69 CO2 emissions in a year of operation; it is equal to planting 2.2 trees.

To determine the CO2 emission reductions produced by the Stand-alone PV System, the emission factor (established by the National Interconnected System, SIN) for renewable energy projects was used. This system is based on the "Tool to calculate the emission factor for an Electricity system" from the United Nations Framework Convention on Climate Change (UNFCCC). To this end, the UPME, on its official website, reports a CO2 emission factor from the Colombian SIN of 0.374 tCO2 / MWh; It was calculated from the information available in [22].

The reduction emissions are calculated as the product of the emission factor (tCO2 / MWh) of the system and the net energy dispatched by the project's activity:

$$BE_y = EG_{PJ,y} \times EF_{CM,y} \quad (10)$$

Where:

BE_y = Baseline emissions in year y (t CO2/yr)

$EG_{PJ,y}$ = Net quantity of power generation produced and transmitted to the grid as a result of the implementation of the CDM project’s activity in year y (MWh/yr).

$EF_{CM,y}$ = Emission factor of the system, calculated as the average of the operating margin’s emission factor (EFOM,y) and the emission factor of the build margin (EFBM,y), (t CO2/MWh).

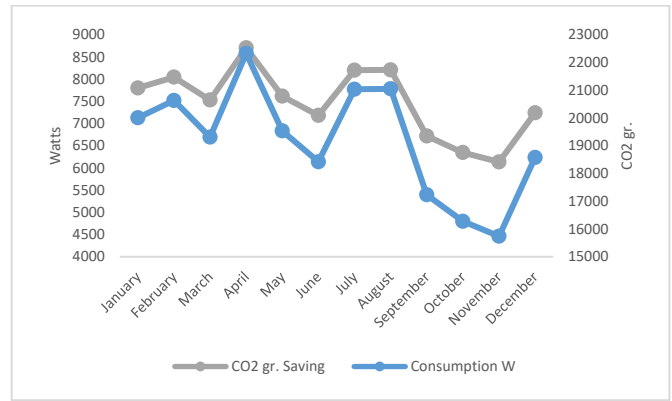


Fig. 9. Relation energy consumption vs CO2 emission reduction during 2016.

By means of an RSC1000 Hall Effect Sensor, the current is detected when the USB device is connected, and the pulse sent by the sensor is taken to perform the connection count. Figure 10 shows the number of beneficiary users with the charging station. In 2016, 5577 mobile devices and 899 laptops were connected.

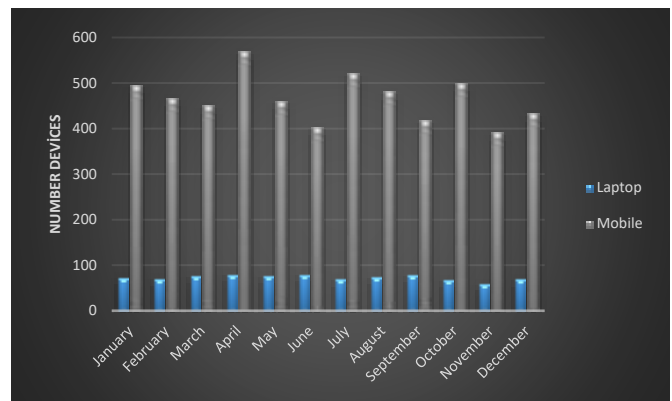


Fig. 10. Number of cellphones and laptops connected to the system in 2016

5. Conclusion

This paper has presented the design and construction of a Stand-alone PV System to charge mobile devices in open urban areas according the environmental conditions of Medellin – Colombia. It integrates (PV) renewable energies and batteries as energy storage and support system. Because of its multiple applications, its natural origin and its social, economic and environmental benefits, Stand-alone PV Systems are a good solution that contribute to problems arising from climate change and the development of alternative energy resources.

The implementation of the Stand-alone PV System contributes to environmental sustainability and helps mitigate the effects

of climate change [23]. In this sense, the prototype presents an emission reduction of 89,758.69 grams of CO₂ during its first year of operation, equivalent to planting 2 trees. In addition, it enhances the urban landscape around it. The results demonstrated that the designed system assures reliable electricity supply for the Stand-alone application under study in this work.

The Stand-alone PV System provides an alternative means of electrification in remote rural communities not connected to the power utility grid. This option reduces the charging cost, provides more environmentally sound sources of energy and therefore, it is more effective in remote rural applications.

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