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Design and Construction Consideration of an Artificial Solar Tree made with Guadua angustifolia to charge Mobile Devices in Medellin

E. A. Duque[1*], P. M. Ortíz[1], A. F. Isaza[1], A. F. Lujan[1], S. Chica[1] and M. Casamitjana[2]

[1]Institucion Universitaria Pascual Bravo, Medellín, Colombia; revistacintex@pascualbravo.edu.co, e.duque@pascualbravo.edu.co, paola.ortiz@pascualbravo.edu.co, a.isaza@pascualbravo.edu.co, a.lujan@pascualbravo.edu.co, sebastian.chica@pascualbravo.edu.co
[2]Universitat de Girona, Placa de Sant Domenec, 3, 17004 Girona, Espana

Abstract

Objectives: This paper presents the design and construction of a solar tree to charge mobile devices on open urban areas according to the environmental conditions of Medellín, Colombia. **Methods/Statistical Analysis:** Based on the electric consumption calculations of mobile devices, a 3.5 m height-tree was built, with four leaves made of acrylic with solar panels on the top. It illuminates with cold white lights and four smaller leaves with green illumination. The energy storage capacity is 180 Amp, it has 6 USB ports to connect mobile devices and two 110 V-200 W electrical outlets to connect those devices to the electricity. Finally, the Photovoltaic system's availability to satisfy the energetic requirements was verified. **Findings:** This research found that according to the established design variables, the system has a 3-hour autonomy on saturation and involves an energy saving of 876 Who, equivalent to 81,645.78 gr saving of emitted CO_2 in a year of operation. **Improvements:** As a final point, environmental, economic and social benefits are presented.

Keywords: Battery Charging Stations, Guadua Angustifolia, Renewable Energy Sources, Solar Photovoltaic System, Solar Tree

1. Introduction

Electricity is one of the basic needs of the modern society and is an essential indicator for economic growth and welfare[1–3]. Electricity access it continues to be one of the globally public policies to reach the objectives of economic social, politic and regional development. Humanity's access to electricity is limited. Over 1.3 billion individuals on the planet do not have it. Also, populated centres do not constitute the most of territories. In fact, more than 84% of the population lives in rural regions in the developing nations[4]. As per[5], having access to power provides a positive influence on the Human Development Index (HDI) and on power utilization per capita, being such access fundamental for human progress in the developed nations.

Last decades, electricity generation has been strongly related to the excessive use of fossil fuels and a high emission of Greenhouse Gases (GG)[6]. Accordingly, the governments and several institutions across the world, promote the use of renewable energies as a prevention tool in view of this fact. Nowadays one of the sources of renewable energy most promising because of being clean, renewable, secure and abundant power is solar energy[7,8]. Solar power is derived from the sun emitted electromagnetic radiation collection by means solar energy pick-ups as thermic collectors or Photovoltaic cells, which transform this radiation on electric or thermic power[9]. In order to meet the current growing power demand (while keeping a low environmental effect), sun power offers an interesting alternative to face this request[10].

**Author for correspondence*

Worldwide researchers have led the quest for finding new clean options for power. The goal is to satisfy the present and future needs[11]. Also, because of traditional power sources scarcity, there is a need for seeking sustainable power sources leading to sound, competitive and renewable economic development around the world, while keeping the planet clean for the generations to come. The current advances in photo voltaic systems have closed some of the gaps between power demand and supply for a variety of new uses[12]. Nowadays, the Earth's power consumption reaches 10 Terawatts (TW) every year. It has been predicted that by 2050, this figure will be around 30 TW. Besides that, the planet will require around 20 TW of non-CO_2 power with the purpose of reducing the CO_2 levels in the air by that year[13].

Electric power has multiple uses and most of them contribute to the well-being of population. Nowadays peoples consume one or two daily hours to charge mobile devices and sometimes there is no available energy charging points to do it, especially in open urban areas. The needs to be constantly informed and connected with other people resulted in the conversion of cell phones and tablets as crucial implements for daily life. According to the report of the Colombian Ministry responsible of ICTs, finalizing 2015, the number of mobile users in Colombia registered were 53,583,664, whereas the inhabitants of Colombia is not more than 48 million. Additionally, according to the report of the industry Colombian Ministry in 2014, realized by the commission of communications regulation[14] the mobile connection are which has highest growth in Colombia, being 58% in 2015. The interest to access to the digital world makes that mobile technology increases exponentially in Colombia, making it the country with the region's fastest growing economy. All these criteria position Colombia in third place using "smartphones" after Brazil and Mexico, according the report on the market penetration of smartphones in Latin America between 2013 and 2018 realized by eMarketed, an specialized firm on digital information[15].

Nowadays, Colombia is a region where renewable energies are experiencing rapid growth[16,17]. There is an increasing interest for the development of this type of project, which has been influenced by diverse factors. One of those is the high prices of electricity in most parts of the region. Others include the increasing power demand, power security issues and in some cases, the potential for electricity exportation. These factors (and others) constitute a suitable framework for the development of renewable energies. This fact is also influenced by the recent decrease of some technologic costs and the growing competition in the sector. The importance of these new alternatives of power generation is that can be an opportunity of sustainable development in Colombia as well as the other Latin-American countries.

Additionally, solar energy systems are being pursued by many countries which have monthly average daily solar radiation level in the range of 3–6 kWh/m[28]. In Colombia, the available source of information of solar resources (IDEAM, UPME) indicates that the average irradiation is 4.5 kWh/m^2/d[18]. Colombian irradiation is higher than the global average (3.9 kWh/m^2/d) and well below the German average (3.0 kWh/m^2/d). It has to be emphasizing that Germany has the highest use of solar power FV at global level, with approximately 36 GW of installed capacity in a 2013[19]. Figure 1 shows the map of Colombia and the Medellín city.

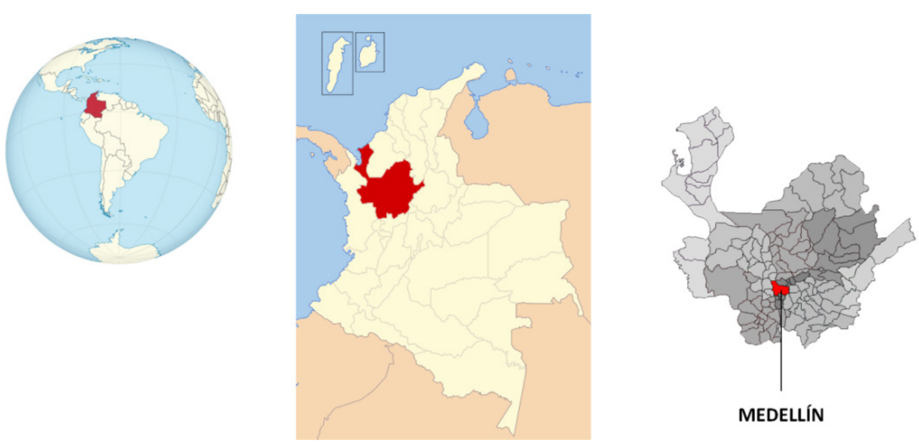

Figure 1. Colombian map and the location of Medellin.

According to the NASA atmospheric science data centre, the monthly averaged insolation clearness index and radiation incident on an Equator-pointed tilted on the location of Medellín Colombia (Latitude 6.217/ Longitude −75.567) as can be seen in Figure 2.

On this paper, the implementation of a solar unit artificial tree is exposed and demonstrates that not only involves economic and environmental benefits, but also allows beautifying the urban landscape. The paper is structured into an introduction, a literature review of the basic concepts of the Photovoltaic concepts and needs, a chapter of used methodologies to design the solar artificial tree and the consumption calculations. The following chapter exposes the implementation, construction of the solar tree design is specified, and the last chapter derives on conclusions about the study of design and construction of the solar tree.

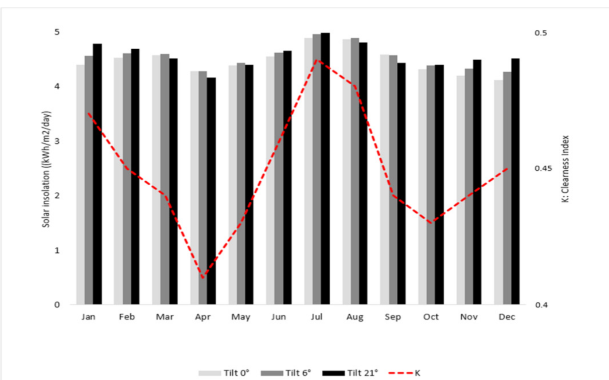

Figure 2. Monthly averaged insolation clearness index and radiation incident on Medellin (Col).

2. Material and Methods

2.1 Solar Photovoltaic System (PV)

The solar Photovoltaic system has played a very important and critical role in the electrification of the rural areas, especially, in the developing world[12]. PV systems used for power generation consists of several combinations of series and parallel PV modules[20]. The sizing of a stand-alone PV system depends upon the performance and the best balance between cost and energy availability[21]. The solar radiation is a very useful design tool for the PV system.

As shown in Figure 3 a stand-alone solar PV system has: Photovoltaic array (solar panels), solar charge controller, storage system (battery banks), power inverter, electronic regulation and control system.

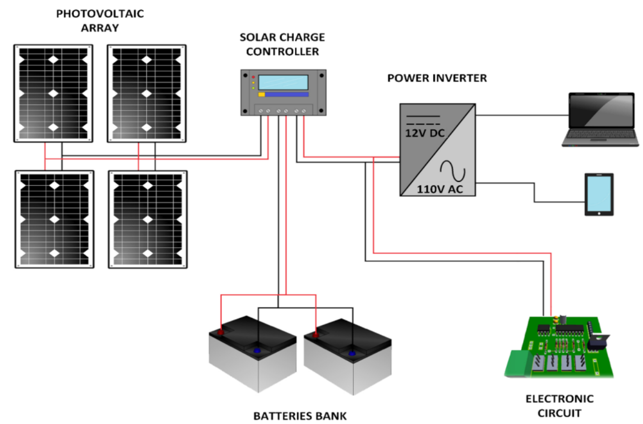

Figure 3. Diagram of the Photovoltaic system of the solar tree.

2.1.1 Photovoltaic array

One of the most important and used means for transforming the energy provided by the Sun is through the use of solar cells. These can directly transform this endless source of power[7]. Combining solar cells with the same characteristics allow increasing voltage as well as the generated current conforming to the Photovoltaic module. The necessary current and voltage is generated by what is known as a Solar Panel; a set of various electrically parallel-attached components[22]. To determine the performance of the solar cell the following factors are considered: Determination of the degradation components related with the design and assembly of the Photovoltaic panel; the environmental conditions to consider as the temperature effect on the solar cell operation; Calculation of the output power of the solar panel.

The current market offers a wide variety of materials for building the Photovoltaic solar cells[12]. The highest performance is provided by materials such as viz crystalline semiconductors, Si and GaAs. Obviously, these types of materials are more expensive than the ones offering lower performance such as viz polycrystalline, amorphous inorganic or even organic materials. A combination of the former ones is also possible[23].

2.1.2 Solar Charge controller

The basic function of this mechanism is to avoid electrical discharges or battery overloads. It is used to protect charges on extreme operation conditions and to bring information to the user.

In order to prevent battery overrun or inadequate currents, a charge controller set controls the voltage from a Photovoltaic module[24–26]. This controller has an additional purpose; it disengages the direct current load from the batteries in order to avoid them from over discharging. The function of charge regulation ideally would have to depend on the charge state of the battery.

2.1.3 Batteries Bank

A batteries bank is needed to store the solar generated energy by the Photovoltaic system and use it in case of absence of solar radiation. The most commonly used energy storage device is VRLA (Valve Regulated Lead Acid)[27]. A battery to be used in a stand-alone solar PV system is charged during sunny hours and must withstand deep discharge during the no-sun hours; such batteries are called deep cycle battery.

2.1.4 Inverter

Due to Photovoltaic panels supplies direct or unidirectional current, when those panels are illuminated by the sun, it is required to convert this electric continue current to alternate current by means of an inverter. His function is too adequate the characteristics of the generated power to the required characteristics of the installation. The main characteristics to consider are input voltage, full power output and efficiency.

3. Design of the Artificial Solar Tree

The sizing of a Photovoltaic system has the main aim to calculate the elements of the system to determinate the electric consume to accomplish it. The methodology presented in this paper shows several activities that can be arranged as follows:

Step 1. To estimate the total consumption.
Step 2. To calculate the optimum solar panel's angle of inclination.
Step 3. To determine the storage system (batteries bank).
Step 4. To determine the size of the Photovoltaic system.
Step 5. To estimate the Solar Charge controller.
Step 6. To determine the size of the inverter.
Step 7. To calculate the required wiring.
Step 8. To design the illumination's control system.
Step 9. To design the battery's indicator status.
Step 10. To design the solar tree with Bamboo.

Step 1. Estimation of Energy Consumption

To design the solar Photovoltaic system, it is necessary to know the total potency of the charges that was connected to the system and like this to determinate the daily power that was needed by the artificial solar unit.

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

$$E_T = \sum_{i}^{n} W_i * h \qquad (1)$$

Where:

E_T = Theoretical required energy (Wh).
W_i = Nominal power of the equipment i (W).
h = Daily use (h).

On Table 1 it can be seen the consume calculations. This operation was realized according the potency sum, considering the amount of each device and the working use.

Table 1. Consumption calculation of the artificial solar tree considering full charge

Description	Units	Potency	Daily use (h)	Total
Cellphone (10 w)	6	10 W	5	300 Wh
Computer (65 w)	2	65 W	4	520 Wh
Illumination big leaves	4	8 W	1	32 Wh
Illumination small leaves	4	1 W	6	24 Wh
			E_T	**876 Wh**

From this value the real energetic consume must be calculated, considering various factors of energy loss into the Photovoltaic installation, according the following Equation 2.

$$E_R = \frac{E_T}{R} = \frac{876Wh}{0.809} = 1{,}083Wh \qquad (2)$$

Where:

E_R = Real power (Wh)
R = Global electrical performance of the Photovoltaic installation, which is calculated by means of the Equation 3.

$$R = 1 - \left(1 - kb - kc - kv\right) * ka * \frac{N}{D_d} = 0.809 \qquad (3)$$

Where:

ka = Self-discharge coefficient.
kb = Coefficient of losses due to the efficiency.

kc = Coefficient of losses due to the inverter.
kv = Coefficient of other losses.
D_d = Discharge Depth.
N = Days of autonomy of the system.

Step 2. To Calculate the Optimum Solar Panel's Angle of Inclination

To benefit the maximum amount of direct sunlight is necessary to determine the inclination degree of the solar panels, characterizing the system in the worst-case scenario of monthly solar radiation. In the site of study Medellin, Colombia, (Latitude 6.217/Longitude –75.567) the month with lower radiation is April at rate of $4.16\frac{\text{kWh}}{\text{m}^2}$ per day and an inclination of 0°[28].

Step 3. To Determine the Storage System (Batteries Bank)

To determine the size of the storage system is necessary to estimate the number of days that the system must be able to operate without solar power and the percentage of maxim discharge that can reach the batteries. To determine the storage system is used the Equation 4.

$$C_B = \frac{E_R * N}{V * D_d} = 180Ah \quad (4)$$

Where:
C_B = Capacity of the batteries of the system (Ah).
E_R = Real power (W).
V = Solar-panel voltage (V).
D_d = Depth of discharge (%).
N = Days of autonomy of the system (day).

Finally, after determinate the nominal capacity several batteries to connect on parallel to obtain a bank of batteries, to support the system with the required autonomy. The number of required batteries is determined by means of the Equation 5.

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

Where:
N_{bat} = Number of required batteries
C_B = Capacity of the batteries of the system (Ah)
C_F = Capacity of the batteries in accordance with factory standards (Ah)

In the case of study, the capacity of the batteries is 90 Amperes and 2 batteries (type AGM VRLA) are needed.

Step 4. To Determine the Size of the Photovoltaic System

To design the Photovoltaic system 10% of power losses are considered, counting with an energy generation higher than the calculated consume. Additionally, it was also considered that in Colombia there is between 4 and 6 daily hours of solar irradiation and to calculate the number on solar-panels needed, it was established an irradiation of 4 hours/day. The following equation shows the calculations realized:

$$N_p = \frac{E_R}{P_p * P_{\max} * h_{ps}} = 4 \quad (6)$$

Where
N_p = Number of solar-panels needed by the system.
E_R = Real power (Wh).
P_p = Percentage of losses by the solar-panel (%).
P_{max} = Maximum potency of the solar-panel (W).
h_{ps} = Daily rush hours of irradiation (h).

For the system 4 panels of 50 Watts/panel on parallel was installed. These panels were located into the uppest part of the big leafs of the artificial solar tree. Additionally, 24 panels (15 Watts/panel) of mixt configuration were installed into the small leafs with green light to locate the solar tree during the night.

Step 5. To Estimate the Solar Charge Controller

Dimensioning the controller, the maximum power of the Photovoltaic system was determined, by means of the calculation of the controller capacity with the Equation 7

$$I_{\max} = I_{SC} * N_p = 3 * 4 = 12A \quad (7)$$

Where:
I_{max} = Maximum current of the system (A).
I_{sc} = Short-circuit current intensity of the solar-panel (A).
N_p = Number of solar-panels.

Having into account that commercially the controllers doesn't have this capacity, a 20 Amperes controller was used.

Step 6. To Determine the Size of the Inverter

The inverter was defined according the power needed by the system as AC, as is exposed in Equation 8.

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

Where:

P_{inv} = Inverter power (W).

P_{AC} = Power needed in alternate current (W).

The power needed by the charge on alternate current corresponds to 2 computers of 65 W approximately, which involves that the inverter power needed is 130 W. It was selected a commercial inverter of 200 W, realizing an over dimension of the system to grants the required power.

Step 7. To Calculate the Required Wiring

To calculate the required wiring is important to consider wiring length due to the losses that can suffer by means of Joule effect and minimizing the lengths and like this avoiding the tension falls and then insuring a minimal resistance. The Equation 9 represents the relation between the section and the wires length.

$$S = \frac{p * L}{R_{ps}} = 1.08mm^2 \tag{9}$$

Where:

S = Wire conductor section (mm^2).

L = Wire conductor length (m).

p = Wire conductor resistivity ($\Omega.mm^2/m$).

R_{ps} = Photovoltaic system resistance (Ω).

It was considered a wire of copper AWG18 with a section of 1.08 mm^2.

Step 8. To Design the Control System

The artificial solar tree was designed and built with an illumination that works during the night hours and an automated control of the illumination by means of proximity sensors and photoelectric sensors was installed, to detect the presence of the users of the unit as well as the luminic intensity of the environment, respectively. This design was divided into three stages:

- First stage: The absence of solar light is detected by means of a LDR sensor as main element and an operational as voltage comparator, where two signs are evaluated (one sign from the voltage devisers and another sign by the LDR sensor). When there is incident sunlight, the sensor LDR makes a sign of low, whereas there is not light incident gives a high sign, which produce an output sign determined on the circuit as LDR sign and finally is coupled and processed by a microcontroller PIC 16F628A. The Figure 4 shows the schematic photoelectric sensor controller of the PV solar system.
- Second stage: The connection of the optic sensors is realized, which allow to identify the presence of people under the artificial tree and sends a sign to the microcontroller, as shown in Figure 5.
- Third stage: The LDR sign and the optic sensors signs are derived to the PIC microcontroller 16F628A where an algorithm is created and whereas of this a decision is taken: turn on the lights of each leaf of the tree if there is absence of sun light and interrupt the optical sensor sign due to a human presence. The Figure 6 shows the scheme of lightening controller connection of the solar tree.

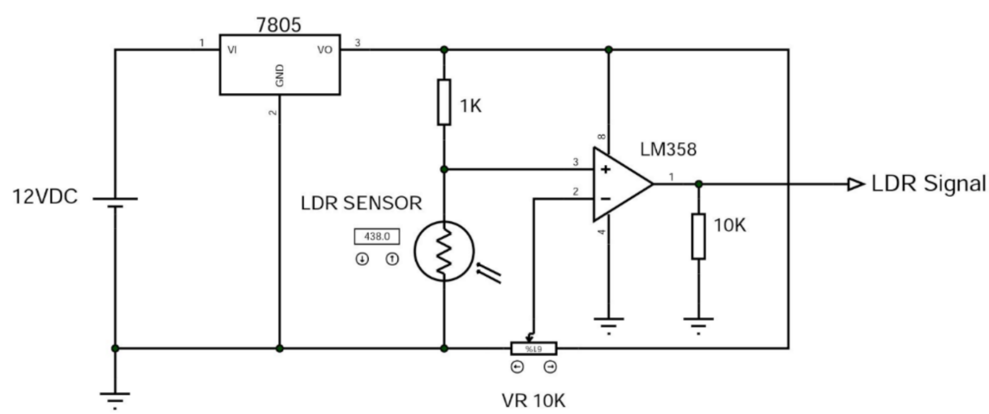

Figure 4. Schematic photoelectric sensor controller.

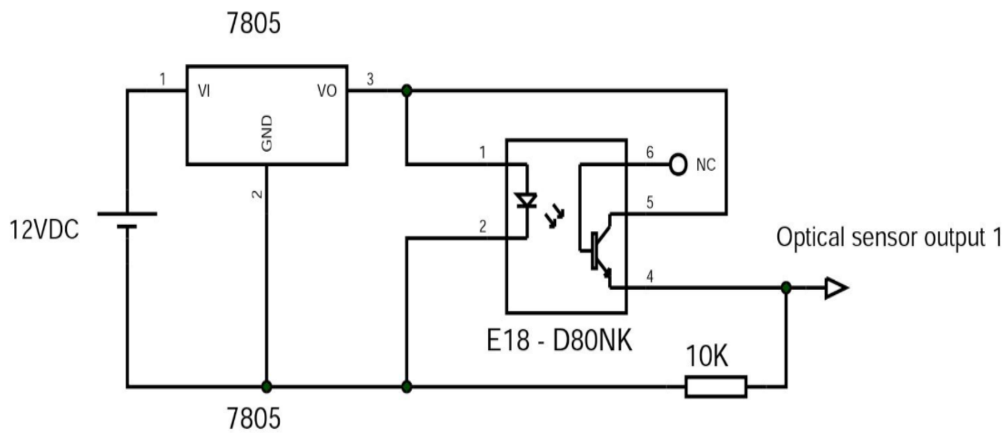

Figure 5. Schematic connection of an optic sensor E18 – 80 NK.

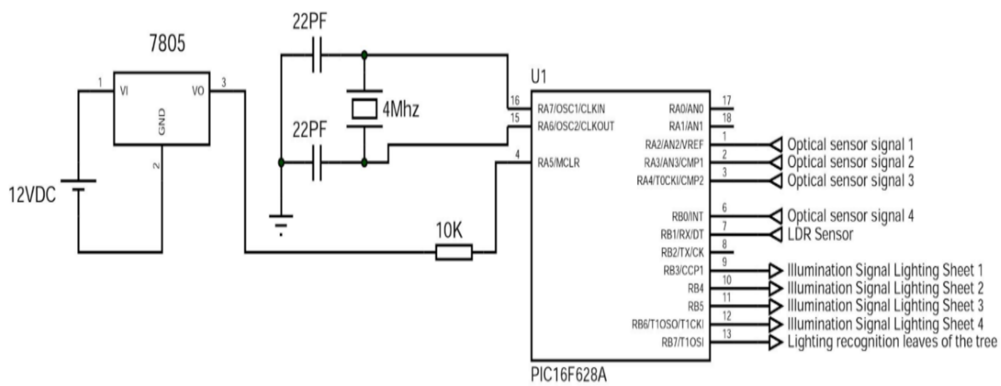

Figure 6. Scheme of lightening controller connection of the solar tree.

Step 9. To Design the Battery's Indicator Status

A target indicator of the battery status that allow visually checking the charge level was installed. This indicator works by means of a led light that indicates approximately a 25% of the battery charge with the main aim to avoid that the storing system reach the minimal percentage of discharge. In Figure 7 the Scheme of the connection system of the battery's indicator status can be seen.

Step 10. To Design the Solar Tree with Bamboo

From the calculations realized, the artificial solar tree was designed by means of Solid Edge ST9, SOLIDWORKS 2017, LuxionKeyShot 6, CorelDRAW X8 and Microsoft Visio 2016, to simulate the shape and location of each

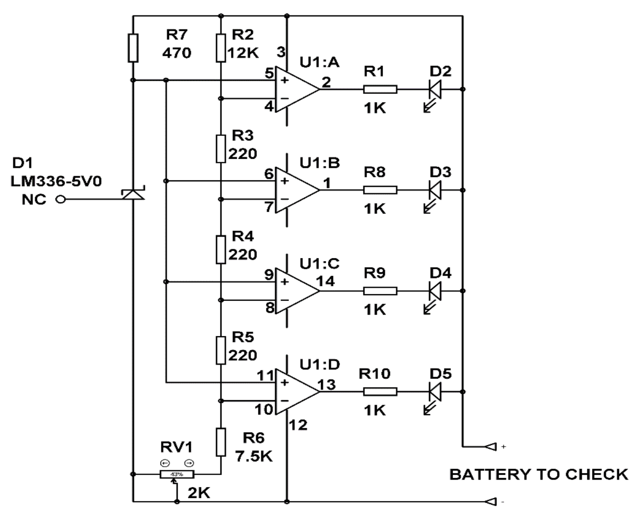

Figure 7. Scheme of the connection system of the battery's indicator status.

component as well as the selection of the building materials, as shown in Figure 8.

The building material of the solar tree was designed according the economic, environmental and physico-chemical properties, determining Guadua angustifolia as the best option[29]. Its light weight and high flexibility can be mentioned as main properties. Additionally, is a porous material with fibers axially arranged which give mechanical and physical properties directionally dependent. Guadua angustifolia has a circular shape and an internal void section, which involves light weight and easy to carry and to store and if the design is the appropriate the resistance to compression and tension are high. The connection of structural parts cannot be realized on the bases of the splices. The Guadua angustifolia or bamboo structures must be designed to work as articulated bars and obtain the maximum efficiency. Bamboo is a renewable natural resource that can be harvested throughout the year. Therefore, metallic connections were designed to increase the physical characteristics of Guadua and facilitate the splices. Additionally, Guadua had a coating to grant his durability and resistance to the climatic and environmental conditions (moisture; temperature, insects).

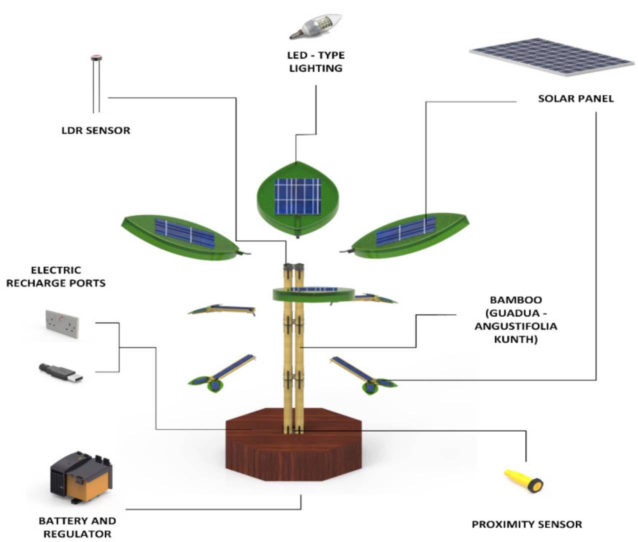

Figure 8. Design of solar tree.

4. Results and Discussion

After having the design parameters stipulated, the solar tree construction was given out with Guadua due to the criteria before mentioned. The Figure 9 shows the real image of the solar tree prototype installed in the Pascual Bravo University in the Medellin City.

The solar tree had 3.5 m height and was built with four leafs made on acrylic with solar panels on top (50 W sized 54 × 83.2 cm) to illuminate with cold white and four small leafs with green illumination and an octagonal steel and immunized wood bank was built. This bank accomplishes the function of support of the structure and as seat for the users.

The prototype of solar tree has the following technical characteristics:

- Voltage of the system: $12V_{DC}$
- Storage capacity: 180 Ah (two batteries 90Ah with dimensions 30.7 × 16.9 × 21.5 cm).
- Current inverter: 200 W.
- Charge controller: 20 A.
- Capacity of use: 6 USB ports to connect mobile devices, 2 current points of charge for computers (110 V – 200 W).
- Autonomy on power saturation: 4 horas.
- Battery's indicator status (Verde 100%, Yellow 75%, Yellow 50%, Red 25%)
- Total height 3.5 m.

The prototype was installed into the university Pascual Bravo, in Medellin and several proves were realized on 2016 to estimate the energy consume by means of charge of mobile devices, number of benefited users, energetic saved to the university and decrease of atmospheric CO_2. To validate the results of energy generation of the prototype, an electronic controller of continue current was installed (nominal tension of 5–800 V DC referenced MK-DC/MK-SH-DC) which allow to identify the consumption of the equipment charged by means of the solar tree unit. From monthly data average, the solar tree has a consumption of 209,375 W, equivalent of a saving of 81,645.78 gr of emitted CO_2 estimating one year of operation, which is equivalent to plant 2.085 trees.

To determine the saving of CO_2 emissions that produces the solar tree, it's necessary the Emission factor of the Colombian Interconnected National System (SIN), for projects that work on renewable energies, which is based on the document established by the United Nations convention of climatic change named "Tool to calculate the emission factor for an electricity system", To this end, the UPME, on its official website, reports a CO_2 emission factor from the Colombian SIN of

0.374 tCO_2/MWh; it was calculated from the information available in[30].

The reduction emissions are calculated as the product of the emission factor (tCO_2/MWh) of the system and the net energy dispatched by the project's activity:

$$BE_y = EG_{PJ,y} * EF_{CM,y} \tag{10}$$

Where:

BE_y = Baseline emissions in year y (t CO_2/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 ($EF_{OM,y}$) and the emission factor of the build margin ($EF_{BM,y}$), (t CO_2/MWh).

On Figure 10, the consumption data of the solar tree and its correlation with the atmospheric CO_2 emitted can be seen.

By means of a hall effect sensor RSC1000, the current passage was detected when an USB device is connected and records the pulse that sends to the sensor to count the connections. On Figure 11 the amount of users of the solar tree, can be seen. On 2016 5236 mobile devices and 910 laptops were connected.

Figure 9. Real image of the solar tree.
Source: photograph of the solar tree prototype installed in the Pascual Bravo University.

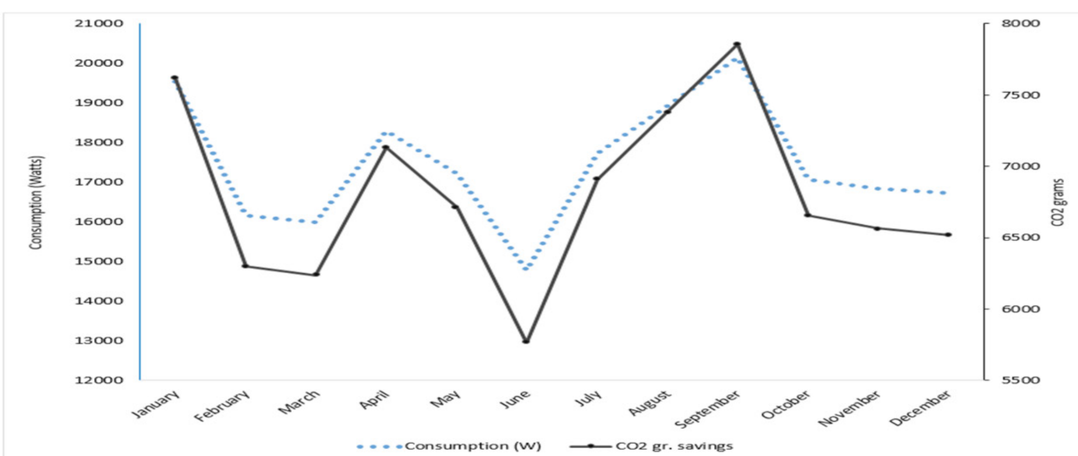

Figure 10. Power consume (W) vs. atmospheric CO_2 saving emission (gr) on 2016.

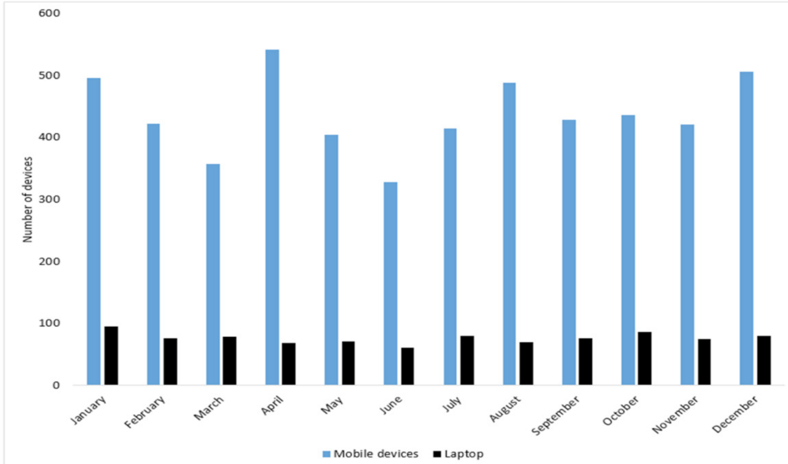

Figure 11. Number of cell phones and laptops connected to the solar tree system during 2016.

5. Conclusions

Photovoltaic solar energy constitutes a viable alternative as storing system to charge mobile devices, especially on rural zones, isolated. Many remote villages in Colombia are not yet connected to grid due to the high costs and the longer distances. The PV systems are believed to be an interesting alternative as pre-electrification schemes.

This paper has presented the design and construction of an artificial solar tree to charge mobile devices on open urban areas, according the environmental conditions of Medellín city in Colombia. Because of the multiple applications, its natural origin and its social, economic and environmental point of view benefits, artificial solar tree is a good solution that contributes to problems reduction arising from climate change and the development of alternative energy resources.

The implementation of the artificial solar tree contributes to the environmental sustainability and helps to mitigate the effect of the climatic change. In this sense, the prototype built involves a reduction of CO_2 atmospheric emissions (81,645.78 grams) during the first year of use, equivalent of planting 2 natural trees and beautifies the urban environment. Furthermore, the number of users of the solar tree was 5236 mobile devices and 910 laptops.

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