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RESEARCH ARTICLE

DEVELOPMENT OF SOFTWARE FOR SIZING AN STAND-ALONE PHOTOVOLTAIC/BATTERY SYSTEM BASED ON MATHEMATICAL MODELS

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Abstract

Photovoltaic (PV) energy is one of the most reliable and ecological sources of electricity generation. Photovoltaic systems are currently being used to supply electricity to isolated areas, away from the principal grids, and can be cost-effective and ensure energy security. Optimal sizing of PV systems in remote locations is a crucial challenge. It must take into account the irradiation of the study area, the tilt angle of the modules, the energy demand and the characteristics of the system components. This work develops software for sizing isolated solar PV power generation systems with battery energy storage. This software is a free offline desktop application that is developed based on empirical equations for sizing the components of a PV system. The languages java (Netbeans) and SQL (SQLite) are used to design the graphical interface and the database respectively. The jasper report plugin was integrated into Netbeans to design the report. The 3040kWh/day load profile of the Kankan Coura health centre, Kankan, Guinea was used to validate the software. Based on this data, the simulation results showed a south-facing tilt angle of 11°, a peak power of 790Wp, a 160Ah battery bank, a 60A charge controller, a 0.5kVA inverter and a cable with a cross-section of 25mm². The results also specified a configuration of 3 series of 2 modules for the PV array and a row of 2 batteries for the battery bank.

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Introduction:-

Nowadays, electricity is essential in the socio-economic development of every nation. All sectors of human life depend on it [1]. However, it is a rare commodity for much of the world's population, particularly in Sub-Saharan Africa (SSA). Already in 2021, the electrification rate is around 60% in the Economic Community of West African States (ECOWAS) area [2]. Most of the energy produced comes from fossil fuels (oil, natural gas and coal) which cause environmental pollution leading to global warming [3, 4]. According to the World Health Organization (WHO), an estimated 4.2 million people die prematurely every year as a result of air pollution, and climate change will lead to an extra 250,000 deaths every year from 2030 to 2050 [5]. For the survival of our species, the use of renewable energy sources (RES), namely solar energy (SE), wind energy, biomass, hydropower and geothermal

energy from natural energy sources could solve the problems of energy crisis and global warming for a sustainable and green future [4, 6, 7, 8, 9]. Among all these RES, SE is seen as the most plentiful form of energy and available in all regions of our planet [7]. Photovoltaic (PV) energy has become a major source of alternative energy in the electricity sector [10]. It is obtained by converting sunlight into electricity [11] via a photovoltaic module. The latter is a set of solar cells connected in series and/or parallel, whose operation is influenced by climatic conditions and the geographical position of the installation site [12-16]. Its efficiency depends on its operating temperature and the irradiation of the site [17-19]. The biggest obstacle to PV energy production systems is the intermittency of its source, hence the need to size PV system components [1, 5]. Due to advances in science, there are various simulation software tools available, such as PVsyst, PV Planner, HOMMER Pro, etc., for sizing PV systems [20-25]. However, these software tools are not accessible to everyone due to their price and the fact that they require a high-speed internet connection. Making free sizing software that does not require an internet connection available to everyone (PV equipment vendors, independent buyers and installers) will help to reduce the failure rate in solar PV installations. The aim of this work is to develop optimal sizing software for isolated PV systems. Specifically, the aim is to design a calculator for each of the sizing elements of a PV system, namely the daily energy consumption, the peak power required, the number of modules and energy storage batteries, the amperage and voltage of the charge controller, the cross-section of the DC cables and the tilt angle). To this end, the paper is structured as follows: section II is devoted to a description of the methodology, the results and discussions are dealt with in section III and the conclusion in section IV.

Methodology:-

The adopted methodology is structured as follows:

- Mathematical models of dimensioning.
- Design of the new software.

PV array sizing

Sizing the entire PV system in an isolated site requires knowledge of a large number of parameters (solar radiation, ambient temperature and wind speed, consumption profile)[27]. In this study, we used RETScreen software to find these meteorological parameters.

-Total daily energy

The daily energy consumption (E_{cons}) of a given site is calculated by equation 1 [33]:

$$E_{cons} \left(\frac{Wh}{Day} \right) = \sum_{i=1}^N P_i(W) * N_i * t_i \left(\frac{h}{Day} \right) \quad (1)$$

With:

$P_i(W)$ is the rate power of an electrical device, N_i is the number of device types and t_i is the usage time of the device.

-The installed peak power

The corresponding peak power (P_c) in Wp of the photovoltaic generator is determined on the basis of the total daily energy consumption, all losses in the system and the average daily solar radiation according to equation 2 [27, 28, 29].

$$P_c(Wp) = \frac{E_{cons} * I_0}{I_i * D_{ep}} \quad (2)$$

With:

I_0 is the irradiance in standard test conditions (STC) which is worth 1kWh/m², I_i is the average daily irradiation of the study location and D_{ep} is the set of total losses (loss in the power lines, the inverter, the charge controller and the battery) recorded in the system. Its value is between 0.55 and 0.75 [27, 28].

Figure 1 shows the influence of irradiation on the electrical characteristics (current - voltage) of the PV module.

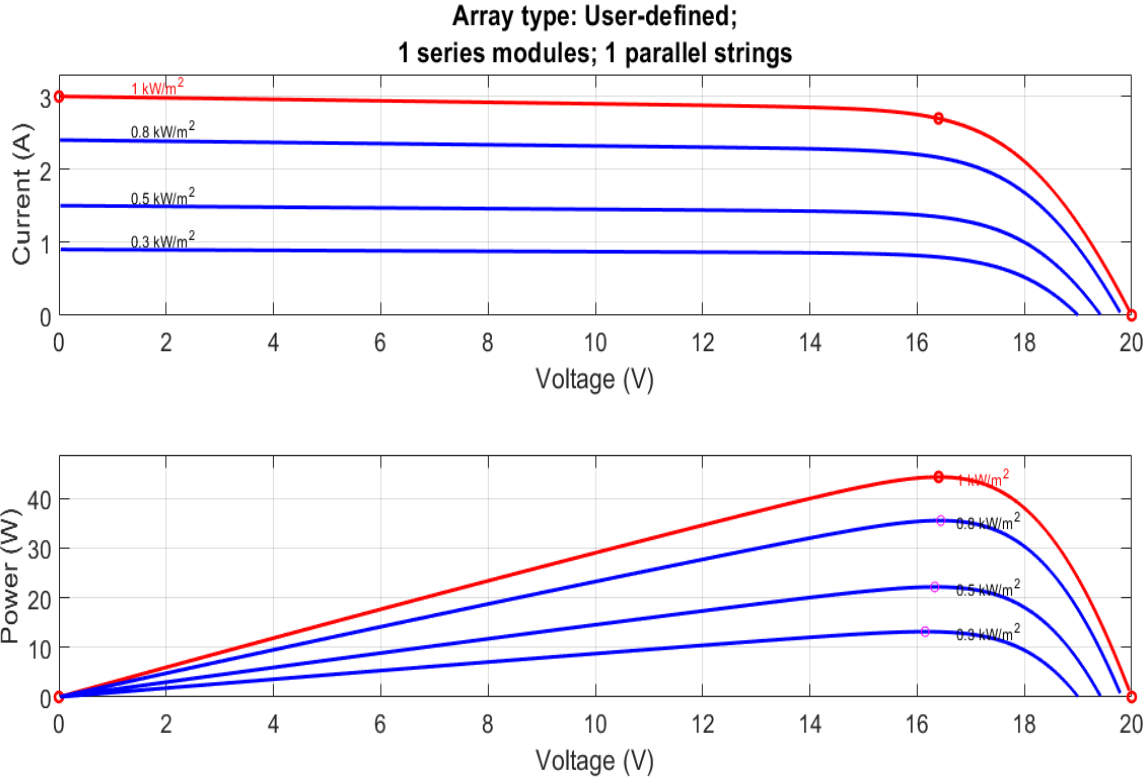


Figure 1:- Effect of irradiation on the power of a PV module.

-Total number of PV modules

Given the value of installed power and the model of the PV module, the total number of modules (N_{PV}) of the PV field is calculated by equation 3 [28].

$$N_{PV} = \frac{P_c}{P_{panel}} \quad (3)$$

With:

P_{panel} is the peak power of a PV module.

-Number of series modules: N_s

The number of modules connected in series in a PV array is given by equation 4.

$$N_s = \frac{U_{sys}}{U_{mpp_module}} \quad (4)$$

With:

U_{sys} is the installation voltage of the PV system and U_{mpp_module} is the voltage at the maximum power point of a module available from the supplier.

-Number of modules in parallel N_p

The number of strings connected in parallel in the PV field to obtain the desired power is given by equation 5 [33]:

$$N_p = \frac{N_{PV}}{N_s} \quad (5)$$

Battery bank sizing

-Battery bank capacity

The battery bank storage capacity is determined based on the number of days of autonomy by equation 6 [27, 28, 29, 33]:

$$C_{st} = \frac{E_{cons} \cdot A_{ut}}{\eta_{bat} \cdot DoD \cdot U_{sys}} \quad (6)$$

With:

C_{st} is the battery bank storage capacity (Ah), A_{ut} is the number of days of autonomy expected for the system, η_{bat} is the battery efficiency and DoD is the desired depth of discharge.

-Number of batteries in series

The number of batteries connected in series (N_{bat_s}) to obtain the system installation voltage is determined by equation 7 [8, 30, 33]:

$$N_{bat_s} = \frac{U_{sys}}{U_{bat}} \quad (7)$$

With:

U_{bat} is the voltage of a battery storage.

-Number of series in parallel

The number of battery strings is obtained by equation 8 [8, 33]:

$$N_{bat_p} = \frac{C_{st}}{C_{bat}} \quad (8)$$

With:

C_{bat} is the unit battery capacity.

-battery's total number in the fleet

The battery's total number N_{bat} required for a fleet is expressed by equation 9 [8, 28]:

$$N_{bat} = \frac{C_{st}}{C_{bat}} * \frac{U_{sys}}{U_{bat}} \quad (9)$$

Sizing of the charge controller, inverter and cable section

-The regulator

The size of a charge controller depends mainly on two factors: the total short-circuits current and the total open-circuit voltage of the PV array. However, it is strongly recommended to increase the current and voltage by 25 to 30% of their total values. The input current of the charge controller ($I_{in_charger}$) is determined by equation 10 [31]:

$$I_{in_charger} = \frac{I_{max}}{K_{temp}} \quad (10)$$

With:

$I_{max} = N_p * I_{sc} * 1.3$, I_{sc} is the short-circuit current of a PV module and K_{temp} is the temperature derating factor of the inverter which is 0.8 in this study [31]:

-Inverter

The power of an inverter expressed in VA is calculated by the formula given by equation 11:

$$P_{inverter} (VA) = \frac{P_{total} * 1.3}{\cos\varphi * K_{temp}} \quad (11)$$

With:

$$P_{total} = \sum_{i=1}^N P_i(W) * N_i$$

P_{total} is the total power of all electrical loads and $\cos\varphi$ is the power factor of the inverter [31].

-Cable section

The cable section depends not only on the length of the cable but also on its resistivity (ρ), the total current (I_{max}) flowing through it, the voltage at its terminals (U_{sys}) and the voltage drop (ϵ). It is calculated by equation 12 [32]:

$$S = 2 * \frac{\rho * l * I_{max}}{\epsilon * U_{sys}} \quad (12)$$

-Determination of the tilt angle

For a PV solar panel to receive the maximum possible sunlight in a latitude zone Φ , it must be tilted at an optimal angle β_{opt} determined by equation 13 [33]:

$$\beta_{opt} = 3.7 + 0.69 \Phi \quad (13)$$

Design of the new software

The database design.

The database for this project is designed in SQLite. It is named 'bd_solution_solr.sqlite' and comprises ten (10) tables (device, consumption_details, daily_consumption, standard_section, simulation_result, project, site, users, pv_module and battery) as shown in Figure 2 of the relational model below. The model is produced in MySQL Workbench version 6.2 CE

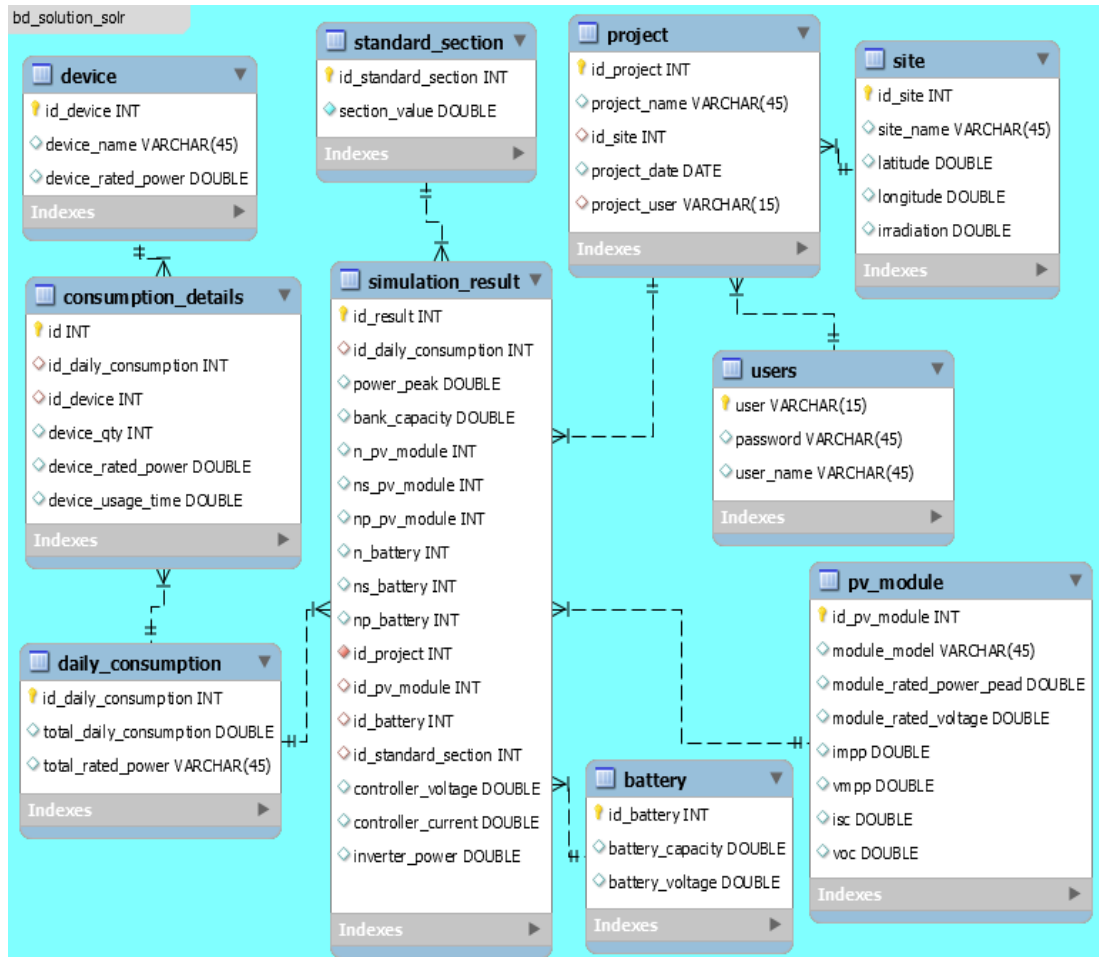


Figure 2:- Relational model of the 'bd_solution_solr' database.

Graphical User Interface Design

The configuration adopted for this software is a Pentium with 512 MB RAM. The system runs in single-user mode under Windows XP, Windows 7, 8, 10 and more recent versions. The database part of the software is based on SQLite, a DBMS that can be embedded on mobile systems. It was chosen here because of the portability of the software, which means it can be deployed on any workstation without the need to install a database server. NetBeans IDE version 7.4 was used to design the software's graphical user interface. The software comprises four (4) windows accessible via buttons: Project definition, Definition of daily energy requirements, Sizing of PV modules and energy storage batteries and Sizing of charge controller, inverter and DC cable cross-section. The sizing algorithm used in the software is illustrated in the figures 3&4.

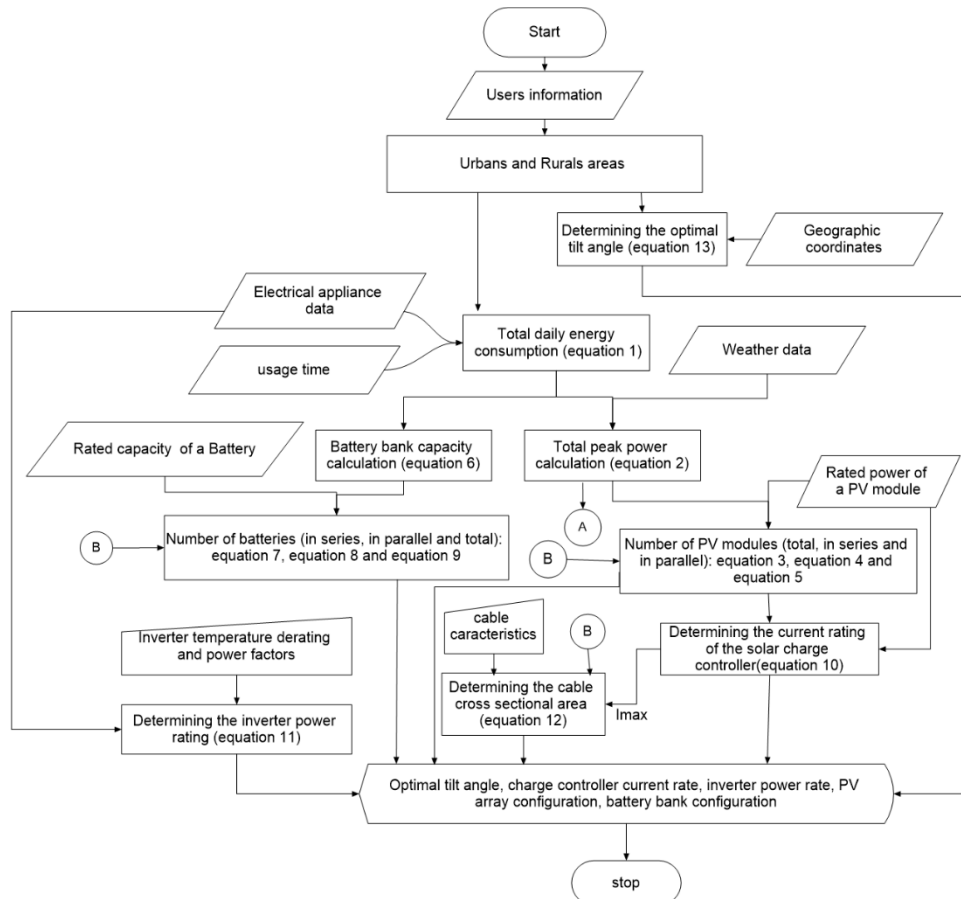


Figure 3:- Flowchart 1 for execution of the whole sizing process.

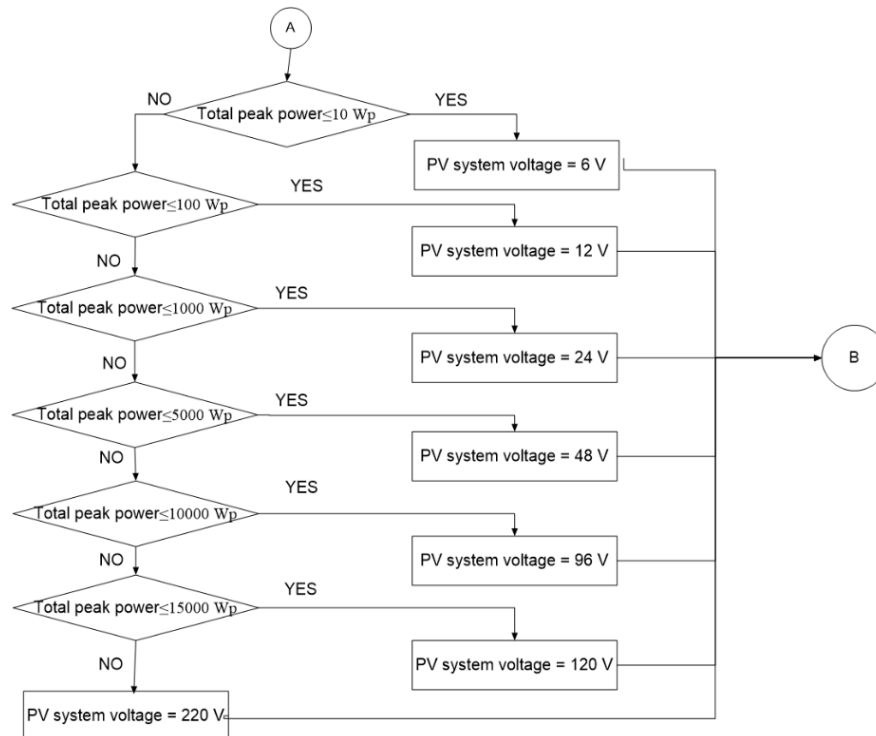


Figure 4:- Flowchart 2 for calculating the PV system optimal voltage.

Results and Discussion:-

Software validation: Case study

The case studied in this paper for the validation of the developed software is a health centre located in Kankan Coura, in the Urban municipality of Kankan, Republic of Guinea. The dimensioning processes are described in the following steps:

Step 1 consists in giving title to the dimensioning project and in choosing the study site; this allows to find the latitude, the longitude, the irradiation of the place and the tilt angle and orientation of the PV field (see figure 5).

Figure 5:- Tilt angle determination.

Step 2: this is the load profile definition step. In this section, the user selects the devices concerned from the list and defines their power ratings, numbers and usage times. This will allow both the total power and the total daily energy consumption to be calculated. The Kankan Coura health centre contains several types of electrical device, an extensive list of which is given in Figure 6.

| Device | Rated Power | | Quantity | Usage time | | Daily energy./day(Wh) | |
|-------------------------|-------------|---|----------|------------|---|-----------------------|----|
| DC 12V/24V solar fridge | 65.0 | W | 1 | 24.0 | h | 1560.0 | Wh |
| DC fan | 10.0 | W | 5 | 8.0 | h | 400.0 | Wh |
| Printer | 21.0 | W | 1 | 1.0 | h | 21.0 | Wh |
| Desktop PC | 60.0 | W | 1 | 8.0 | h | 480.0 | Wh |
| DC energy saving lamps | 3.0 | W | 12 | 14.0 | h | 504.0 | Wh |
| Phone charger | 5.0 | W | 5 | 3.0 | h | 75.0 | Wh |

Figure 6:- Calculation of total power and total daily energy consumption.

Step 3: In this step, PV array peak power, battery bank storage capacity and system installation voltage are calculated directly by the software. The user can choose a PV module and battery model available from his supplier. This will allow the user to find the total number, in series and in parallel of the PV module and battery.

According to the total daily energy consumption obtained in step 2, the configuration of the PV array and the battery bank of the health centre of Kankan Coura is illustrated in figure 7.

Figure 7:- PV array and battery bank configuration.

Step 4: This is the final sizing step, which involves determining the ampere rating and the charge controller voltage, the cable cross-section and the power of the inverter. The values for the inverter and charge controller temperature derating factor, the charge controller voltage drop and the inverter power factor are already incorporated into the software. All the user has to do is define the length of the DC cable (10 m in this study). The load profile defined in step 2 and PV field and battery bank configurations allow the software to obtain the values shown in Figure 8.

Figure 8:- Sizing the charge controller, inverter and cable cross-section.

After the last step, the software automatically manages the simulation report presenting all the details of the study project. This report is a kind of specification for the system installer. It provides information on the tilt angle of the modules and the characteristics of the charge controller, the inverter and the connection cable between the PV array and the battery bank. In addition, the installer will find the type, number and configuration of the modules in the PV



SolutionSol'R

| | | | | |
|--------------------------|----------------------------|----------------------|------------|-------------------|
| Project | KANKAN COURA HEALTH CENTRE | | | |
| | Number : | 24 | Date : | 2025-03-04 |
| | Author : | Ibrahima FOFANA | | |
| Site locality | | | | |
| Place : | | Kankan, GUINEA | | |
| Latitude : | | 10.3833° N | | |
| Longitude : | | -9.3° W | | |
| Irradiation : | | 5.5 kWh/m²/day | | |
| Optimal tilt angle : | | 11 ° | | |
| Orientation : | | South | | |
| System configuration | | | | |
| Peak power : | | 790.0 Wp | | |
| Bank capacity : | | 160.0 Ah | | |
| System voltage : | | 24.0 V | | |
| PV module | | Battery | | |
| Number in serie : | 2 | Number in serie : | 2 | |
| Number in parallel : | 3 | Number in parallel : | 1 | |
| Total number : | 6 | Total number : | 2 | |
| Charge controller sizing | | | | |
| Type : | | MPPT | | |
| Maximum input current : | | 44.0 A | | |
| Maximum input voltage : | | 59.0 V | | |
| Inverter sizing | | | | |
| Type : | | MPPT | | |
| Inverter rated power : | | 0,5 kVA | | |
| Cable sizing | | | | |
| Cable type: | | Copper | | |
| Cable length : | | 10.0 m | | |
| Cable cross section : | | 25.0 mm² | | |
| Charge profile | | | | |
| Device | Power | Qty | Usage time | Daily consumption |
| DC energy saving lamps | 3.0 W | 12 | 14.0 h | 504.0 Wh |
| Printer | 21.0 W | 1 | 1.0 h | 21.0 Wh |
| Phone charger | 5.0 W | 5 | 3.0 h | 75.0 Wh |
| Desktop PC | 60.0 W | 1 | 8.0 h | 480.0 Wh |
| DC fan | 10.0 W | 5 | 8.0 h | 400.0 Wh |
| DC 12V/24V solar fridge | 65.0 W | 1 | 24.0 h | 1560.0 Wh |
| Total rated power : | 257.0 W | Total daily energy : | | 3040.0 Wh/day |

Conclusion:-

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PV/battery system with 6 modules (2 in series and 3 in parallel) and 2 batteries in series with a charge controller and an inverter of 60A and 0.5kVA respectively.

In the future, we intend to improve the software by integrating the calculation of the investment cost and the amount of carbon dioxide that can be reduced by a PV system.

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