

# Sizing a solar cell array for a solar powered lawnmower machine

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## Abstract

This project focuses on the sizing and control of a photovoltaic (PV) collector of a solar lawnmower prototype to satisfy the geographical orientation of Puerto Rico and its available sunlight. The design, analysis and construction of a Solar Powered Lawnmower prototype were performed to obtain an electrical device powered by a renewable and ecology friendly source of energy. Photovoltaic technology reduces the use of fossil fuel and increases the safety of the mowing operation. Complete mathematical modeling and computer simulation of the components of the Solar Powered Lawnmower machine (power system, driving, photovoltaic modules, frame/chassis, steering system) was performed so as to have the lowest possible energy consumption, which at the same time would have a direct influence on the sizing of the photovoltaic cell arrays or PV collector. After completing the computer model of the proposed solar lawnmower, a prototype design was built and tested.

## Sinopsis

### Cortadora de grama solar

Este proyecto trata sobre cómo determinar el tamaño y el control de los arreglos de celdas solares o colectores de un prototipo de cortadora de grama que satisface la orientación geográfica de Puerto Rico y la cantidad de luz solar disponible. El diseño, el análisis y la construcción del prototipo de cortadora de grama solar se hicieron con miras a obtener un dispositivo solar competitivo usando una fuente de energía eléctrica que fuera renovable y compatible con el medio ambiente. La tecnología fotovoltaica reduce el

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consumo de combustible fósil y aumenta la seguridad en la operación de cortar la grama. Se realizó un completo modelaje matemático y simularon en la computadora los componentes de la cortadora de grama solar (sistema de potencia, transmisión, módulos fotovoltaicos, estructura/chasis y sistema de dirección) con el objetivo de tener el consumo de energía más bajo posible de energía, lo cual tiene una influencia directa en el tamaño de los arreglos de celdas solares o colector solar. Una vez se completaron los modelos en la computadora del diseño se construyó un prototipo y se realizaron pruebas.

### Introduction

In 1988, the United States sponsored the Long-Range Transboundary Air Pollution Agreement, and ratified a protocol freezing the rate of nitrogen oxide emissions at 1987 levels. The 1990 amendments to the Clean Air Act of 1967 set regulations to reduce the release of sulfur dioxide from power plants to 10 million tons per year by January 2000. This amount is about one-half the emissions of 1990.

The new environmental policies, and other controls established, stress the search for alternative energy sources. The challenge, therefore, is to convert solar energy technology into a key power source for everyday devices in the measure that problems of resource availability and environment quality increase.

### The photovoltaic system (PV)

A photovoltaic system consists of an assembly of interconnected solar cells (cell array) which produce direct current (DC) electricity when exposed to sunlight. Generally, cell array are connected in series and in parallel to obtain appropriate levels of current,  $I$ , and voltage,  $V$ . Most cells are made from ultra-high purity silicon with cell conversion efficiency about 14%. Amorphous silicon cells provide lower cost but also have lower conversion efficiency. Gallium arsenate (layered multi-junction) cells for high-efficiency devices are being investigated.

### Electrical characteristics of a solar cell

The electrical characteristics of solar cells are represented with the current voltage (I-V) relationship, as shown in figure 1. The I-V curve relates the solar cell's output current and voltage from a short circuit (zero resistance) to an open circuit (infinite resistance), measured under standard testing conditions.

As figure 1 shows, the maximum power, voltage and current must be specified under the working conditions, that is, temperature and solar radiation of the solar cells.

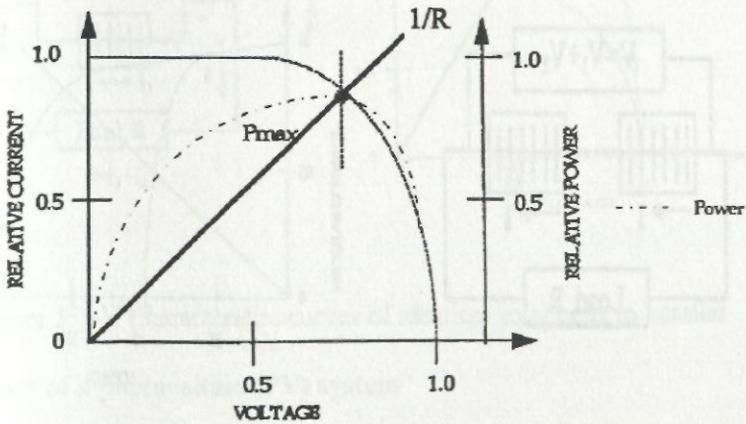


Figure 1. I-V Characteristic curve of a solar cell

The standard operating conditions (SOC) or peak rating corresponds to a solar cell temperature of 25°C, an irradiance (solar radiation) of 1000 w/m<sup>2</sup>, and wind average velocity of 1m/s.

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### Identical solar cells connected in series

Considering an electric resistance element connecting two nodes in a DC circuit, Ohm's law gives the relation between the current,  $I$ , entering the element, the voltage drop,  $V$ , and the resistance,  $R$ , as  $V=RI$ . The resulting current-voltage,  $I$ - $V$ , characteristics of two identical solar cells connected in series can be deduced from the characteristics of each individual cell, adding the voltage,  $V_1$  and  $V_2$ , for the same current,  $I$ . As shown in figure 2, the resulting characteristics of cells with identical performance connected in series is obtained by adding the  $I$ - $V$  characteristic curve at the same current level.

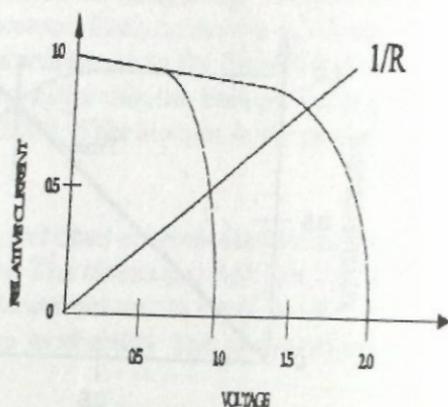
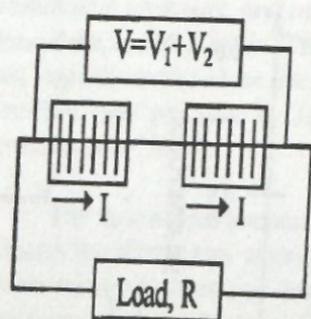


Figure 2. Characteristic curves of solar cells in series

### Identical solar cells connected in parallel

The  $I$ - $V$  characteristics curve of two identical solar cells connected in parallel is determined by considering the circuit shown in figure 3. The resulting voltage,  $V$ , is the same for each individual cell and the resulting current,  $I$ , is obtained adding the respective current,  $I_1$  and  $I_2$ , of each cell.

As figure 3 shows, the resulting characteristics of cells with identical performance connected in parallel is obtained adding the I-V characteristic curve at the same voltage level.

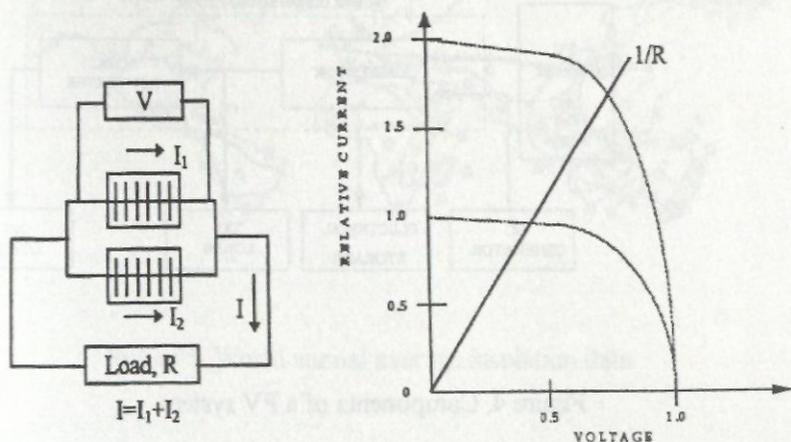


Figure 3. I-V Characteristic curves of identical solar cells in parallel

### Elements of a photovoltaic (PV) system

Figure 4 shows the major components of a PV system. The cell array provides the DC electrical power needed. The power conditioning subsystems convert the DC electrical energy into the appropriate form to supply the load.

In the design of the solar lawnmowing machine only DC power is used, which means that a AC/DC converter is not required. The electrical storage (i.e, batteries) is the backup power system used when sunlight is unavailable during the night or cloudy days.

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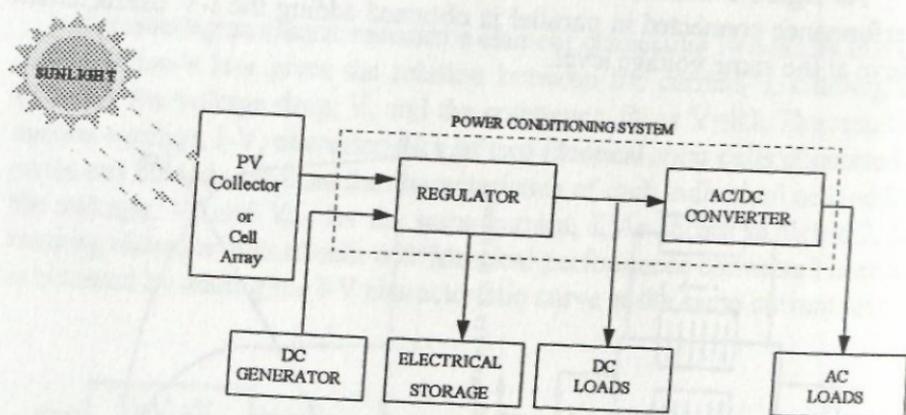


Figure 4. Components of a PV system

### Insolation data

Figure 5 shows the world annual average insolation conditions. The geographic orientation of Puerto Rico corresponds to area A with an average solar radiation collected of about  $4.5 \text{ Kwh/m}^2 \cdot \text{day}$ , measured horizontally. Average insolation values are based on recorded data considering the 12 monthly values including those days with partial recording.

The lines running through the map represent those sites with similar solar energy availability; that is, these data represent average conditions for a day at any time of a year. Each letter labeling the lines refers to the kilowatt hours of solar energy striking on one square meter of ground or horizontal surface in a day.



Figure 5. World annual average insolation data

### PV system performance

The overall system efficiency (Module Efficiency) is the product of the PV collector efficiency and the efficiency of the support devices: power systems control and conditioning, electrical storage, wiring, tracking, and regulators. In this project we used solar cell array with a basic cell efficiency of 16.5%. Taking into account the optical losses in the module, the module packing factor, and the effect of average annual cell temperature (30°C), the module cell efficiency is reduced to 13.4%. This efficiency is obtained by using equation (1) as follows,

$$\eta_m = \eta_c \eta_T \eta_{SOC} \eta_p \quad (1)$$

where

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- $\eta_m$ : Module efficiency under operating conditions
- $\eta_c$ : Basic cell efficiency
- $\eta_T$ : Optical transmission efficiency, measured through encapsulated materials to cell
- $\eta_{soc}$ : Module efficiency under standard operating conditions as previously defined
- $\eta_p$ : Module packing efficiency

In this project, the following values were used:  $\eta_c = 0.16$ ,  $\eta_T = 0.96$ ,  $\eta_{soc} = 0.92$ ,  $\eta_p = 0.92$ . For the effect of the supporting devices, 2% loss through the wiring was assumed, and 12% loss in energy for the power conditioning. In this case, the power conditioning was used to reduce the voltage level output from 17.3 V to 12 V, that is, voltage output from the cell array to input motors of the solar lawnmower. Therefore, if we consider an average solar radiation condition of 4.5 Kwh/m<sup>2</sup> day in Puerto Rico, under the previous conditions and assumptions, a power equivalent to 585 Wh/m<sup>2</sup>day will be available at the output.

### Sizing the cell array for the solar lawnmower machine

The first step for sizing the cell array is to calculate the load or energy consumption. The load can be expressed in Watt-hours (Wh). A current of one ampere running for one hour at a voltage level of 1 V is 1.0 Wh. Mathematically, this is expressed as:

$$E_c = V I t \quad (2)$$

where,

$E_c$ : Energy consumption, Wh

$V$ : Voltage level, V

$I$ : Current, A

$t$ : Time, hr/day

An estimation of how much current is drawn by all the connected devices must be made, and how long, on the average, each device will run, the voltage level and the duration of the operation. In the design of the prototype lawnmower, two motors were used. One for driving the machine (transmission system) and a second one for the cutting device. Table 1 gives the electric characteristics of these motors.

Table 1. Characteristics of the lawnmower motors

	Operating voltage (V)	Current (I)	RPM
Transmission Motor	12	1.5	140
Cutting Device Motor	12	1.3	13,500

These were the only electrical consumption (load) for the solar cells array considered. (The remote control used was powered by two AA batteries, included in the purchased package). It was assumed that the lawnmower would be in continuous operation during 4 hours/day. Thus, from equation (2), the corresponding energy required for the motors is = 134.4 Wh/day. Also, a safety factor of 15% was used considering an unattended, accessible site. Thus, the energy consumption (load) considered for sizing the cell array is finally 154.5 Wh/day.

The next step is to select an appropriate arrangement of cells, series and parallel, to obtain 154.5 Wh/day. Round cells with 4.75 in. diameter were used. The area of the cells is, therefore, 17.7 in<sup>2</sup> (0.011 m<sup>2</sup>). As table 1 shows, the cell array must be capable of giving a current level of 2.8 A or higher and

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a voltage level of 12 V. Unfortunately, a module with these electrical characteristics was not found commercially at the design time. The construction of a module of individual cells connected in series and parallel was the solution to this problem. However, we recommend acquiring a module with the specified electrical characteristics from manufacturers. Table 2 presents the specifications from the manufacturer of the solar cells selected (specified at an average solar radiation of 1000 W/m<sup>2</sup>.day).

Table 2. Electrical characteristic of individual solar cells<sup>1</sup>

Open circuit voltage	2.4 V
Maximum power voltage	1.92 V
Short circuit current	1140 mA
Maximum power current	1040 mA
Rated power	2.0 W
Encapsulated solar cell efficiency	16.5%

<sup>1</sup> Rauschenbach, H., 1980, Solar Cell Array Design Handbook, Van Nostrand Reinhold Co., New York.

Considering identical solar cells with the electrical characteristics shown in table 2 and following the I-V characteristics curve shown in figure 2, we constructed a cell array of 7 cells connected in series to obtain a maximum voltage level of 13.4 V. Similarly, from figure 3 and using the electrical characteristics shown in table 2, a set of 4 arrays connected in parallel gives a maximum current level of 4.16 A. Therefore, a total of 28 solar cells are required for a total energy output of 223 Wh/day, which satisfies the demand of energy of 154.5 Wh/day.

### Conclusion

We built and tested a prototype of a solar lawnmower machine which is capable of converting the incident light (solar radiation or irradiance) to electric power (DC power) in a suitable structure, thus eliminating the dependency on fossil fuel to power the machine. To evaluate the performance of photovoltaic systems it is necessary to know the amount of sunlight that can

be collected and its typical spectral distribution and how this is influenced by atmospheric conditions. Unfortunately, the existing insolation data available for Puerto Rico have several drawbacks: these data are available for a limited number of sites and have questionable reliability and accuracy basically because of the time spacing between the data acquisition. As a result of this project, an experimental study is proposed as an alternative to analyze the insolation data required and to compare them with existing collected data.