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A specific Photovoltaic Panel for an Ultra-light Electric Vehicle focused on Urban Mobility

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Abstract

Nowadays, electric vehicles are considered the best alternative to achieve sustainable urban mobility. However, the extended implementation is conditional to a sufficient number of charging stations and the design of a new power grid distribution. Indeed, the vehicle model that dominates the current market, electric or thermal motors, is ten times heavier than its useful weight (occupant plus luggage), so it is not efficient in the way it uses the energy.

In this article, an ultra-light electric vehicle with his own photovoltaic generator is proposed as an adequate vehicle prototype for sustainable mobility. This kind of vehicle does not need many charging stations and, because of that, the implantation is less complex than for other commercial vehicles.

To verify this proposal, a specific photovoltaic panel was designed, manufactured and evaluated for this kind of vehicles. It can reach a specific power of 27.24 W/kg in STC, higher than commercial solar panels. An experimental study in a wind tunnel was conducted in order to know the influence of the photovoltaic generator in the drag coefficient, and to calculate the performance of the vehicle in an urban circuit.

The most important results are that the vehicle, at STC, can circulate at a maximum speed of 35 km/h, without the need to charge the battery from the grid. For the same conditions, if the vehicle circulates at the maximum speed allowed in urban circuits, 50 km/h, it would have a range of 200 km per kWh charged from the grid.

Keywords: Urban mobility; Electric Vehicle ; Stand-alone PV system

1 Introduction

The current urban mobility model is as follows:

- The private vehicle energy consumption represents about 50% of the consumption on highway transportation in Spain. The remaining percentage is composed basically by freight traffic (about 47%) and the remaining minimum to multiple passenger transportation (3%).
- All Spanish cities taken into account, about the same number of trips are made in private and public transportation.
- Per litre of gasoline consumed, a car has an average emission of 2.3 kg of CO_2; and the emissions per litre of diesel are about 2.6 kg of CO_2. In 2012, transportation contributed to a 20.1% of the total CO_2 emissions in the European Union (EU, 2014).

Regarding the use of private vehicles for urban transportation:

- 50% of the trips are shorter than 3 km
- 10% are shorter than 500 m
- Over 75% of the trips are made with a single occupant
- The average number of passengers is of 1.2 people per vehicle

In this context, the use of the electric vehicle (EV) for the urban mobility appears as a viable alternative to solve these problems, due to they don't produce urban contamination, they can be fed by 100% renewable energy and the electric engine are more efficient than the internal combustion engine [1].

However, the implementation of the EVs also has disadvantages. For example, it is needed to improve and increase charging points locations around the city, and for that, it is needed to redesign the electric grid of the cities [2].

A variety of solutions to overcome this problem has been proposed: The development of little hybrid vehicles [3] or light EVs and tricycles [4]-[5]. It is interesting the concept of Light electric vehicle (LEV) [6]. The characteristics of this kind of vehicles are:

- Single occupant
- Weight lighter than 100 kg
- Tricycle (2 front wheels and 1 rear wheel)
- Speed limited to 70 or 80 km/h
- Operation voltage less or equal to 48 V

To compare the performance of each kind of urban vehicle, the "efficiency in the mobility" has been defined as follows [6]:

$$ef\,fmobility = (ef\,fsystem)\cdot\frac{usef\,ulweight}{total\ weight} \qquad (1)$$

The values of this efficiency for several types of vehicles are the following:

- 1% for an internal combustion engine with a 14% of performance, a weight of 1300kg and an useful weight of 100kg (1 people of 80kg each one and a 4kg of baggage)
- 6,7% for the EV i-Miev, with a 80% of electric engine performance, a weight of 1100kg and an useful weight of 100kg
- 32% for a LEV with a 70% of electric engine performance, a weight of 100kg and an useful weight of 84kg (a person and his/her baggage, 4kg)

These results show that the LEV concept is most appropriate than other types of vehicles for obtaining a sustainable urban mobility. Nevertheless, for the development of this model of urban transport it is necessary to install a wide network of charging stations, and it can cause a high impact in the electric power supply of the cities. There are different solutions for that; for instance, one is based in renewable energy systems to provide energy in restricted areas of the city. Photovoltaic generators could be installed in the University campus to feed students' vehicles such as tricycles, EVs or electric scooters [7].

In this paper we propose a solution for this problem. A stand-alone photovoltaic generator has been designed for charging the batteries of the LEV. This generator will be installed directly on top of the vehicle, so that the need to recharge throughout the day is highly unlikely, and therefore the need for charging-station systems is minimized.

The VEIR14 LEV (Figure 1), developed by the AERO team students from the Industrial ETSI of the University of Malaga to be used in energy efficiency races such as the 2014 Solar Race of the Murcia region, has been used as the base for this project. A specific photovoltaic generator with 170 W of peak power has been designed, built and evaluated to be installed on the top of this vehicle, and data has been obtained from several operating conditions of the generator.

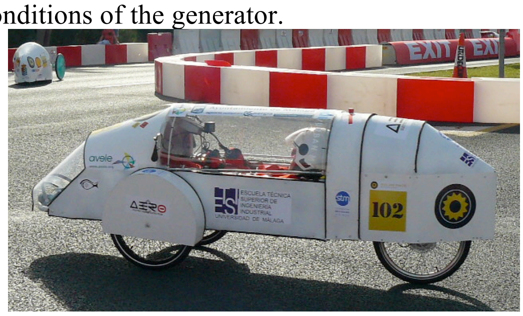

Figure 1: The VEIR14 LEV.

This work shows the design, manufacture and evaluation of a photovoltaic generator for further implementation in the VEIR14. This generator fits to the characteristics of this vehicle, so we will obtain more advantages than installing a commercial photovoltaic module. Three aspects have been considered to optimize the performance of the generator:

- The numbers of cells have been selected to allow the direct connection with the battery, avoiding the need to install electronic load regulators.
- The geometry will adapt perfectly to the dimensions of the vehicle in order to improve its aerodynamics.
- To reduce the overall weight we have used very light materials for the rear layer of the modules.

With the addition of this PV generator, the VEIR14 will extend their range in such a way that the charges from the electric grid will be dramatically reduced.

2 Work Methodology

2.1 Solar Cell characterization

To manufacture the photovoltaic generator we used monocrystalline solar cells of 3 x 6 inches. To get the data of that cell we designed several tests using the following measuring instruments:

- a calibrated photovoltaic reference cell of 5V from ATERSA,
- a regulated power supply, LD300 model, from AIM-TTI INSTRUMENTS,
- and two digital multimeters, DMM 120 model, from MULTIMETRIX.

The main results of the tests are shown in Table 1.

Table 1. Parameters of photovoltaic cell

Irradiance	985 W/m2
Temperature	25ºC
I_{SC}	3,94 A
V_{OC}	0,57 V
I_{MPP}	3,249 A
V_{MPP}	0,47 V
P_{MPP}	1,52 W

2.2 Photovoltaic generator design

Firstly, a study of the characteristics of the battery in the EV was completed in order to proceed with the design. The battery has a nominal voltage of 48V and is formed by 13 lithium-ion cells. A test was conducted to obtain the voltage/state of charge curve of the battery. The result is shown in Figure 2.

The normal work range of the battery is between 70%-30% of its state of charge. In the graphic we can observe that in that range, the drop of voltage is only 2V (50V-48V). To minimize the overall weight and complexity, one of our goals is to connect the batteryx directly to the PV generator, avoiding the use of a charge controller. So, the output voltage of the PV generator in its maximum power point must be between these voltage values.

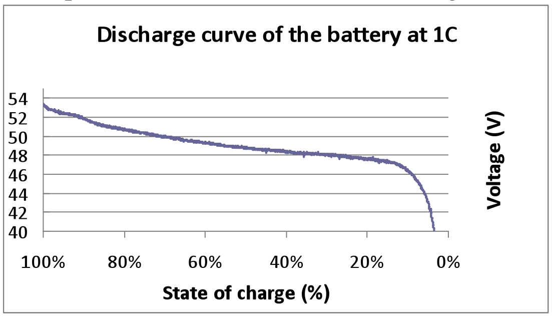

Figure 2: Voltage/SOC curve of the battery

Based on this result and taking into account the voltage of the cell in its maximum power point, the number of cells to make up the photovoltaic generator were calculated as follows:

$$N^{\circ}_{SolarCells} = \frac{Vpanel}{V_{mppsolarcell}} = \frac{50}{0,47} = 106 \quad (2)$$

Another necessary component are the bypass diodes to avoid the "hot spot" phenomenon [8] when there is a shadow on one part of the generator. Otherwise, a shadow in only one cell will nullify the power generated by the generator and can damage it.

To calculate the maximum number of cells per bypass diode, we have measured the zener breakdown voltage of one cell, obtaining a value of 25V.

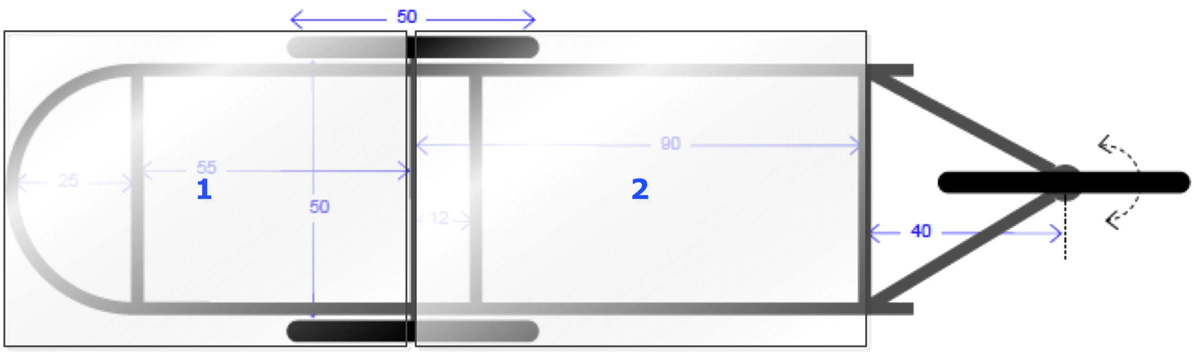

Figure 3: Top of the VEIR14 with the two modules of the photovoltaic generator

Considering that the maximum voltage per cell is around 0,55V:

$$\frac{V_{zener}}{V_{\max cell}} = \frac{25}{0{,}55} \approx 45\ cells \quad (3)$$

It means that theoretically we could have 45 cells per bypass diode. In practice, we set a bypass diode per 20 cells.

To complete the design of the generator, we need to add the blocking diode that doesn't let the current to flow in the opposite direction through the modules.

The next step was to design the geometry of the generator, adapted to the VEIR14. The generator was performed by two photovoltaic modules whose characteristics are shown in Table 2

Table 2. Characteristics of the PV generator

	Module 1	Module 2
Length (mm)	814	900
Width (mm)	800	800
Number of cells	50	55
Structure	5 strings of 10 cells each one	5 strings of 11 cells each one

Noticing that we used 105 solar cells instead of 106 because of design reasons. Figure 3 shows the location of the panels on the vehicle.

Module 1 has been manufactured to evaluate the design. For the rear layer, we used a foam aluminium sandwich. Two layers of EVA film were used for cells encapsulation. The result was a module with a minimum weight of only 3.3 kg.

2.3 Aerodynamic study

The next step was to make an estimation of how the photovoltaic generator affected the aerodynamics of the VEIR14.

After some calculations about the forces against the movement, we know that for a light vehicle the aerodynamic force is the most important. The other forces such as rolling resistance and acceleration are proportional to the weight of the vehicle and when we add the generator it almost doesn't change. The total weight increments only 7 kg.

Aerodynamics cannot be easily estimated because the total coverage of the panels is greater than a square metre. For this reason, a scaled-down model to 1:5 of the VEIR14 was carried out to be able to test-run it in the wind tunnel (Figure 4) and observe different behaviours depending on the setting of the photovoltaic modules on the car frame (height of placement) as well as its comparative to the LEV without the panel.

The result of the study confirmed our hypothesis. The drag coefficient of the vehicle without the PV generator was measured in 0.349 and with the PV generator, a significantly superior value of 0.447 was obtained.

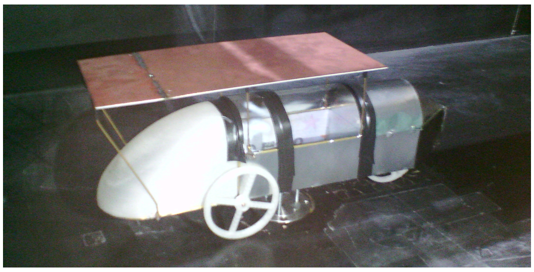

Figure 4: The scale-down model of the VEIR14 with PV generator in the wind tunnel.

2.4 Theoretical evaluation of the performance of VEIR14 with the photovoltaic generator.

To finalize this study, it has been evaluated the behaviour of the VEIR14 with the photovoltaic generator in different conditions of use:

Firstly, the maximum speed estimated to operate without the necessity to do a charge of the battery in the grid, according to the irradiance.

Secondly, the range of the vehicle driving at a constant speed of 50 km/h (maximum speed allowed in the city), according to the irradiance.
Thirdly, a comparison between the performance of this LEV and other commercial EVs has been carried out.

3 Results

3.1 Evaluation of Module 1

To evaluate the performance of the photovoltaic generator, the Module 1 was built and tested. We have used the LD300 electronic load to simulate the battery and a calibrated photovoltaic reference cell to measure the level of irradiance.
Figure 5 shows the system tested.

Figure 5: Module 1 and calibrated photovoltaic reference cell

Taking into account that the generator has 105 cells and the module 1 only 50 cells, to simulate the operation of the generator connected to a battery with voltages between 48V and 50V we have configured the electronic load to operate between 22,8V and 23,81V when it is connected to the module 1.
The photovoltaic generator test was run with a solar irradiance value of 1062.5 W/m^2 and at a temperature of 25 ºC. In these conditions, a short circuit current of 4.14 A and an open circuit voltage of 27.3 V were measured.
Table 2 shows the results of the equivalent output battery voltage, the output panel voltage and the maximum power point (MPP) of the photovoltaic module.

It is remarkable that the MPP is between the two values of simulated output battery voltage. It is a good result because the battery will spend most of the time between that range and not in the extremes (48-50V) nor in lower voltages.

Table 2: Test results of the Module 1.

Module 1 voltage (V)	Output current of the module (A)	Power generated by the module (W)
22.84	3.77	86.11
23.81	3.54	84.29
23.15	3.75	86.81

From these results, we have evaluated the efficiency of the module in standard conditions as 13.54%. We also calculated theoretically the total power of the photovoltaic generator with the two modules at standard conditions as 171.58 Wp.
We also have evaluated another important parameter that is the specific power. That parameter depends on the total power generated divided by the weight of the module. We did a comparison with other commercial modules and we achieve very good results (Table 3).

Table 3: Specific power comparison between several commercial photovoltaic modules and the Module 1

Module type	Power (Wp)	Weight (kg)	Specific power (W/kg)
Module 1	81.7	3.3	24.76
Bosch M60 EU42117	260	21	12,38
BP 4175	175	15,4	11,36
Sunpower-333NE	333	18,6	17,90

3.2 Theoretical evaluation of the VEIR14 with the photovoltaic generator installed on top.

The characteristics of the VEIR14 with the generator installed are the following:

- Total vehicle and generator weight: 48 kg
- Rolling resistance coefficient: 0.005
- Drag Coefficient: 0.447
- Front area: 0.3106 m^2
- Estimated weight of a passenger plus luggage: 80 kg
- Photovoltaic generator power: 171.58 Wp
- Average motor efficiency: 80%

The calculation is done at a constant speed, we didn't evaluate the accelerating force.

Figure 6 shows the maximum speed in which the car could move as a function of the solar irradiance, using exclusively the energy provided by the PV generator.

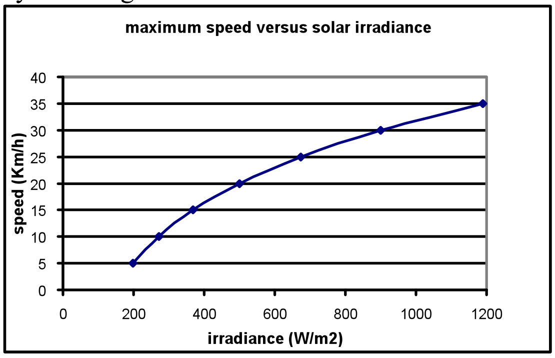

Figure 6: Speed of the LEV as a function of the solar irradiance

From that graph we can deduce that the vehicle has an infinite range when running at constant speed of approximately 35 km/h, in optimum conditions of irradiance. The vehicle could run at a higher speed but the battery must be charged by the electric grid, because the photovoltaic generator won't generate enough energy.

Figure 7 represents the range of the vehicle at a steady speed of 50 km/h per kWh charged from the electric grid.

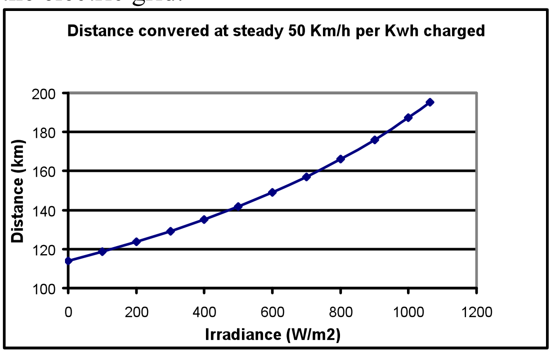

Figure 7: Range of the LEV running at 50 km/h per kWh charged

Lastly, we have carried out a simulation of the range per kWh charged from the grid for some commercial EVs such as the Mitsubishi iMiev and the Nissan Leaf. We estimated a useful weight of 100 kg (1,2 people of 80 kg per one plus 4 kg of baggage). The results are shown in table 4.

This information tells us that even with zero irradiation the range of the LEV proposed in this paper is ten times higher than the commercial EVs.

Table 4: Range per kWh charged from the grid.

Irradiance (W/m^2)	VEIR14 + PV generator (km)	Leaf (km)	i-MiEV (km)
1062,5	195,23	10,11	11,93
1000	187,38	10,11	11,93
800	166,03	10,11	11,93
600	149,05	10,11	11,93
400	135,22	10,11	11,93
200	123,73	10,11	11,93
0	114,05	10,11	11,93

4 Conclusions

This paper shows the design, manufacture and evaluation of a specific photovoltaic generator for a light electric vehicle intended for using in urban mobility. From the results we can get the next conclusions:

- With this kind of vehicle an unlimited range can be achieved when transiting at speeds of up to 35 km/h, in optimal irradiance conditions.
- For greater speeds, it is necessary to charge the vehicle, but the range is still very high, being able to reach the 200 km for a constant speed of 50 km/h.
- Even without solar irradiance, the obtained range is ten times higher than electric vehicles currently found on the market.

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