Improved Performance of a Battery Powered Electric Car, Using Photovoltaic Cells

Angel Abusleme, *Member IEEE*, Juan Dixon, *Senior Member IEEE*, and Daniel Soto.

***Abstract*-- One of the major problems for the massive applicability of Electric Vehicles (EVs) is the scarce capacity of conventional electrical energy storage systems. Although this constraint has been overcome in many cases using advanced technologies such as fuel cells and high-capacity batteries, it is still difficult to develop an economically viable and socially acceptable EV for massive use. In this context, solar energy is not a practical solution for satisfying this lack of energy. However, if a particular situation is considered, in which a small-sized, high-efficiency EV operates at low duty cycles in a sunny, predictable environment, solar power can become a solution for reducing transport costs. This paper deals with the reach of this approach.**

***Index Terms*—Battery Chargers, Photovoltaic Cells, Road Vehicle Electric Propulsion, Solar Energy**

I. Introduction

ONE of the major barriers for the applicability of electric vehicles (EV) is the scarce capacity of conventional electrical energy storage systems. Although 38% of the vehicles sold in 1900 were electric [1], the overwhelming range of internal combustion (IC) vehicles made EVs become relatively impractical for decades.

Technological advances have made it possible for electric vehicles to compete in range with conventional IC vehicles. For instance, the availability of high-capacity zinc-air batteries and high-efficiency brushless DC electric motors [2] have dramatically improved the range of leading EVs; fuel cells have an extraordinary potential as EVs energy sources; finally, ultracapacitors provide EVs with high quantities of power – positive or negative – whenever is required [3]. Previous facts show that the range barrier between electric and internal combustion vehicles is being reduced. However, most of these technologies are still under development and their cost makes them prohibitive for economically viable and socially acceptable EVs oriented for massive use. In this scenario, solar energy [4] is not a practical solution for satisfying this lack of energy, due to the comparatively small power it can deliver and the dependence of its behavior on an uncontrollable factor: weather.

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Although range is an important issue to consider when evaluating a vehicle, it is also a relative figure. Several studies during the last years show that the average commuter travel distance in U.S. cities has been and keeps around 10 miles. In this situation, commuter-oriented EVs can be developed with a reduced load of batteries, and therefore, a reduced power plant. In these conditions, solar energy can be managed in order to produce a palpable contribution to the EV energy source [5, 6].

This particular situation considers a light, small-sized, high-efficiency EV operating at low duty cycles in a sunny, predictable environment. In this case, solar power can become a real solution for reducing commuter transport costs and incrementing range [5]. Energy collected by solar cells located on the vehicle's roof can be an important part of the total energy required by the vehicle when moving or when charging its batteries under all other circumstances. As this approach does not need additional expensive infrastructure, such as a solar net or stationary solar generators, it can only be useful under certain, controlled conditions, and these conditions must be determined in order to evaluate whether this solution yields real improvements in the vehicle performance.

This paper deals with the features of this approach. In first place, the desirable characteristics for the EV and its operation conditions are exposed. Then, some design considerations are analyzed, and finally, the potential of this option is studied.

II. Commuter Solar-Powered EV Energy and Range

In this section of the paper, the necessary conditions for the practical application of the previously presented idea are discussed. In first place, basic radiation considerations are defined. Then, some general parameters of the vehicle such as mass, power, and energy storage capacity are determined. Finally, the EV performance and range, as a function of the previous figures, will be obtained.

A. Basic radiation considerations

Before addressing the vehicle parameters problem, it is necessary to define the amount of energy available for working with. In this case, the most important variable is the insolation on horizontal surface (I_H), defined as the amount of electromagnetic energy (solar radiation) incident on the surface of the earth [7]. This variable is measured in kWh/m^2/day and represents the total solar energy incident over one square meter on the surface of the Earth during one day. In reference [7], it is possible to find charts of this variable for each location of the Earth during the year.

The insolation on horizontal surface has a wide range of values depending on the latitude, season, climate and weather. For example, as the day duration on the poles can be as long as 24 hours and as short as 0 hours, the insolation value in the South Pole is as high as 8.5 kWh/m^2/day in summer, and obviously, 0 kWh/m^2/day in winter.

The insolation anywhere around the world is seldom higher than 8.5 kWh/m^2/day. This means that it is very difficult to find a place which receives more than 8.5 kWh of solar energy in one square meter during one day. When the low efficiency of solar cells is also taken into account (no more than 15% for reasonably low-cost cells), the scenario turns even worse. This means that, assuming a perfect efficiency during the conversion stages, after one day of collecting and storing solar energy obtained in one square meter of 15%-efficiency solar cells, the total energy collected would be about 1.275 kWh, barely enough to turn on a medium-size vacuum cleaner during 1 hour. In the case of a 1800 kg electric truck, this energy is capable of moving the vehicle for only 5 km at a reasonable speed.

Previous example shows why at present, solar energy is only useful as a portable source for low-power equipment, or a stationary source capable of delivering high amounts of power, but not as a mobile high-power source. When required in high-power mobile applications such as electric traction, solutions similar to Park & Charge® system [6] have become available (Europe). This system consists of an extensive number of privately-owned solar collectors connected to a grid, oriented for vehicle charging purposes. If the subscriber needs to travel far away from his/her own solar collector connected to the grid, he/she knows that he/she can charge the batteries in any Park & Charge® outlet available in the grid. Although this is an excellent answer to the solar power mobility problem, it still depends on a high-cost, stationary solar charger grid. Although useful as stationary power source, solar energy is not a practical solution for most high-power mobile applications.

However, there are some applications where the collected energy is significant, specifically in those with high solar-collector-surface-to-consumption ratio. One interesting example of this idea is the Helios Solar Airplane [8], which combines the generation ability of high-efficiency photovoltaic panels with the energy storage capacity of lithium-based batteries. Current works with regenerative fuel cells batteries aim to keep the airplane flying for as long as six months without stops.

Where solar-collector-surface-to-consumption ratio is not high enough, solar batteries contribution for mobile, high power applications is marginal; however, solar batteries can improve the autonomy and eventually, reduce operation costs.

If we think in a solar-powered EV as a box filled with batteries (to store the collected energy), a traction system and a roof covered with photovoltaic panels, a simple conclusion is obtained: when the box grows, the external surface (solar collector) grows with a power of two, and the internal volume (batteries capacity) grows with a power of three. This means that, as the vehicle size increases, the area for collecting solar energy as a percentage of the total vehicle energy capacity decreases. Previous facts imply that the most important contribution of solar energy to a solar EV occurs for small-sized vehicles. For this reason, this paper is centered in the contribution of solar energy to a generic, small-sized EV.

Considering that the EV usage conditions should not be affected by the season, it is necessary to find a location profile that maximizes the vehicle performance. This implies to find a region where radiation is maximized over the entire year, and where its minimum value is high enough to keep improving the vehicle performance. That place must also have clear skies during the entire year.

Deserts and arid regions near equator are eligible as convenient niches for the development of the idea presented in this paper, if they exhibit clear skies and have high insolation levels during the entire year. In order to determine the general vehicle parameters, we will assume that the minimum insolation of the place we will choose is around 4 kWh/m^2/day. If higher, it will help even more with the vehicle performance.

B. General vehicle parameters

In this section of the paper, a rough exercise oriented to the design of a small-size electric vehicle is shown. The exercise is based on energy availability and performance criteria. The objective is to compare its theoretical performance with and without the contribution of solar energy.

The figure of 4 kWh/m^2/day is weak, considering that the vehicle's roof has hard space restrictions and that most common solar cells have efficiencies around 15%. For this reason, it is necessary to maximize the vehicle efficiency. In order to do that, the vehicle considered in this paper should be small, aerodynamic, lightweight, and relatively low in acceleration and maximum speed. For this purpose, a two-person vehicle with a small trunk will be considered.

Most small-sized, high efficiency electric vehicles are very light. For example, Twike has a mass of 220-250 kg, including batteries [9]. Since it is difficult, risky and expensive to design and build a practical car with a lesser mass, it will be considered a 330-kg vehicle, without batteries. In practical electric vehicles, lead-acid batteries have a mass of at least 30% of the entire vehicle mass [2]. This rule can be applied on small-sized vehicles too. In this case, considering 100 kg of batteries, the total vehicle mass should be around 430 kg. If two 75-kg persons were also in the vehicle, the total mass would be around 580 kg.

In order to determine the motor nominal power, it is necessary to define how the vehicle is intended to perform. As a design criterion, it could be defined that the vehicle should be able to move in a 20% slope at a speed of 10 km/h with two persons in it, and reach a maximum speed of 75 km/h in plains.

The power needed to move at 10 km/h in a 20% slope can be calculated using the well known equation (1):

$$P = F \cdot V = mg \cdot sin\theta \cdot V \qquad (1)$$

This yields a power of at least 5400 W. If a 0.92 efficiency factor is considered in the mechanical transmission mechanism, the output power needed is around 5870 W.

In order to reach a speed of 75 km/h (second criterion), it is necessary to determine the aerodynamic drag and the rolling resistance. The aerodynamic drag F_d can be calculated as

$$F_d = C_d \cdot A \cdot V^2 , \qquad (2)$$

where C_d is the coefficient of drag, A is the frontal area and V is the instantaneous speed (assuming no wind) [2]. The coefficient of drag for a small vehicle can be around $C_d = 0.3$. Considering a frontal area of 1.56 m^2 (roughly 1.3 m wide and 1.2 m high), the drag force at 75 km/h is around $F_d = 203.1$ N.

The following expression is a simple approach to calculate the rolling resistance F_r for a vehicle over a flat, concrete surface [2].

$$F_r = C_r \cdot m \cdot g \qquad (3)$$

For most vehicles, C_r has a value near 0.018. This yields a rolling resistance of $F_r = 102.3$ N for the fully loaded vehicle.

The traction force at 75 km/h must match the sum of the drag and rolling resistance forces, this is 305.4 N. To produce this traction force at 75 km/h, the power needed is 6362.75 W. If a 0.92 efficiency factor is considered in the transmission mechanism, the output power of the electric motor should be around 7 kW (nominal). Since this figure is higher than the power needed to climb a 20% slope at 10 km/h, a motor with a power of 7 kW satisfies both criteria.

One of the objectives of this work is to evaluate a low-cost, environmental-friendly mean of transportation. Both features are well achieved if lead-acid batteries are used, because they are relatively cheap and almost fully recyclable. For this reason, deep discharge, sealed lead-acid batteries will be considered. These batteries present a specific energy of 35 Wh/kg for a 3-hour discharge rate (figure pertinent for EV calculations). As the vehicle carries 100 kg of batteries, the total energy is 3505.3 Wh. However, in order to avoid permanent damage, batteries cannot be fully discharged. Considering an 80% deep of discharge (DOD), the total energy available in the batteries is roughly 2.8 kWh.

Using previous figures, it is possible to determine an equation for the vehicle expected range R in a flat, concrete freeway as a function of the speed. The following equations do not consider the contribution of the solar batteries to the vehicle energy:

$$R = V \cdot T , \qquad (4)$$

where T is the total duration of the batteries. Considering a total battery capacity of E_{batt}, a traction force F and a traction efficiency η, the expression for the vehicle range can be written as follows:

$$R = V \cdot \eta \cdot \frac{E_{batt}}{V \cdot F} = \eta \cdot \frac{E_{batt}}{F} \qquad (5)$$

As seen before, the force F can be expressed as the sum of drag and rolling resistance. Finally, the equation for the EV range as a function of its speed is

$$R = \eta \cdot \frac{E_{batt}}{C_r \cdot m \cdot g + C_d \cdot A \cdot V^2} \qquad (6)$$

The value of η can be obtained as the product of the efficiency of each component – batteries, converters, motor and transmission system. Although efficiency depends on usage conditions, it is possible to set this value around 75%. Fig. 1 shows the EV range as a function of the speed, considering the parameters determined in this section.

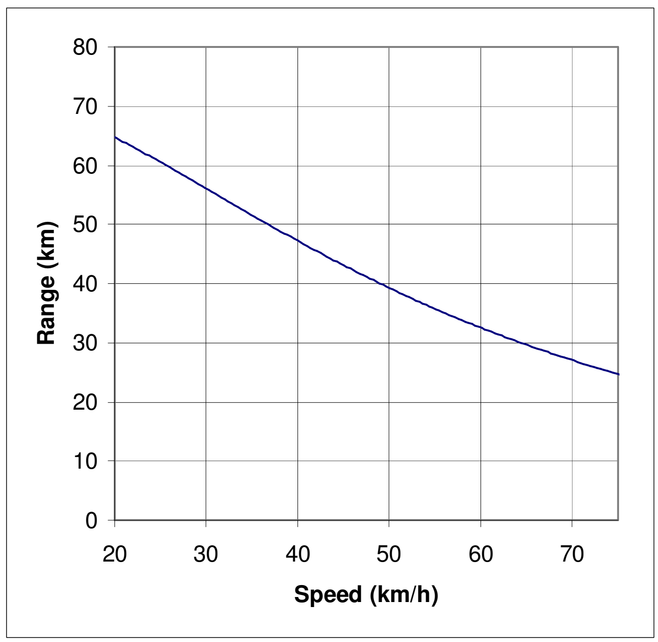

Fig.1. Range as a function of speed in a small EV

As shown in the previous figure, the theoretical range is high enough for a commuter-oriented vehicle, since it considers short trips and long periods for recharging.

C. Contribution of solar energy to a small-size EV

The energy required by the EV to operate depends mainly on its speed. For low or medium speeds, the EV could be able to operate for relatively long distances with low energy requirements, due to its size and efficient design. This makes it possible for solar energy to do a real contribution to the energy available for the vehicle, improving range and reducing operation costs. In this section, basic calculations of the contribution of solar energy to a small-size electric vehicle are presented and discussed.

As a first assumption, it is supposed that the vehicle will be most of the day exposed to the sun, without entering in underground parking lots or tunnels. It is also supposed that the vehicle should have a main solar panel on the roof and a secondary, telescopic panel under the main panel. When circulating, only the main solar panel will generate power; when parked, the telescopic panel should be deployed over the windshield using a rail system, collecting more solar energy.

If the mechanical design is adequate and the panels are set in a platform over the roof, its surface could be 1.82 m^2 (1.3 m width and 1.4 m length), leaving enough space for a significant windshield. The telescopic panel could be half the length of the main panel and the same width, obtaining a surface of 0.91 m^2. With both panels deployed, the vehicle would have a combined collecting surface of 2.73 m^2 (Fig. 2)

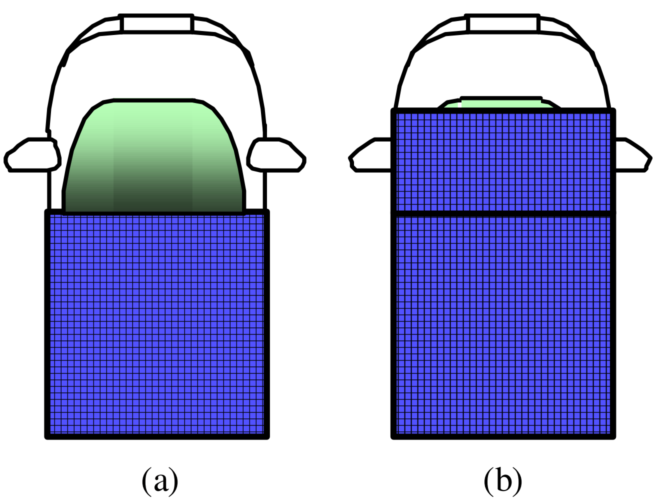

Fig.2 Vehicle top view (a) without and (b) with telescopic panel deployed

Solar generators can be purchased as solar cells or solar panels (arrays of solar cells). Solar panels have a lower efficiency than solar cells, because they have gaps between cells. For this reason, it is recommended to use solar cells in order to build custom solar panels. The panel efficiency can be maximized if square-shaped solar cells are used and the gaps between contiguous cells are reduced.

Most economically viable solar cells have efficiencies around 15%. One example is the Qmax-12-1540, manufactured by Q-cells, with an efficiency of 15.4% [11]. If gaps between cells are reduced, it is possible to build panels with an efficiency of 15%. However, this efficiency is reduced in the process of assembling the panel: solar panels must be completely sealed to avoid deterioration, and the seal has a limiting clearness of 0.92 (Dow Corning® 1-2577 Conformal Coating [12]). This implies solar panels with efficiencies around 13.8%.

During one day of low insolation (I_H = 4 kWh/m^2), neglecting the charge losses (supposing slow charge), the total energy collected by the roof panel W_R can be obtained as

$$W_R = \eta \cdot I_H \cdot A = 0.138 \cdot 4 \cdot 1.82 = 1\,kWh \qquad (7)$$

This amount of energy is only a little more than one third of the available battery bank capacity. During one day of low insolation, if the secondary panel is deployed, the total energy collected by the vehicle W_T is

$$W_T = \eta \cdot I_H \cdot A = 0.138 \cdot 4 \cdot 2.73 = 1.5\,kWh \qquad (8)$$

If the EV is parked and with the telescopic panel deployed during ¾ of the sunny hours, the total energy collected by the panels in one day of low insolation would be around 1.38 kWh, which represents almost half the entire battery bank effective capacity. In high-insolation days (8.5 kWh/m^2/day), this figure can be easily doubled, making it possible to fully recharge the EV batteries in one day using only solar energy. In the best conditions, for an EV that leaves home early in the morning and arrives late at night, the total range could be doubled. Although cost reduction is minimal, the most important conclusion is that the vehicle travels with its own portable solar generator that, when deployed, is able to provide the EV with an important amount of energy whenever and wherever is required.

Finally, it is important to clarify that previous calculations assume solar panels with a constant efficiency. In real solar panels, efficiency increases with light intensity, but decreases with the temperature of the cells. This implies that in a practical application, previous results are optimistic, but near to real values.

III. Design Issues

Although the only possible important element in which a commuter-oriented EV should differ from a standard EV is the solar collector, there are several differences in their respective designs. These differences can be appreciated in weight, battery capacity, power plant, mechanical structure, accessories, etc. In this section, some design considerations necessary for the efficiency maximization of a commuter-oriented EV are presented. In first place, electrical design considerations of this vehicle are exposed. Then, the mechanical design problem is addressed.

A. *Electrical Design Issues*

In this section, more details regarding the electrical implementation and the addition of solar generators to the generic, previously presented small-size EV are exposed.

Before defining the solar panels voltage, it is necessary to set a nominal battery voltage. For a small-size EV (low power and low current), a 60 V battery bank is reasonable. As a solar panel will charge the battery, its output should be above (and always near to) 60 V. However, although a solar panel is able to keep its voltage around the nominal value, its current changes with the incident light, and the power it can deliver may decrease substantially if the panel is not working in its maximum power point [4]. In this case, if the panel were connected directly to the battery bank, its output voltage would be set at the battery pack voltage, and the maximum power point would be seldom (or never) reached.

In order to maximize the solar panel output power, a Maximum Power Point Tracker (MPPT) can be used. The MPPT is a device that combines microcomputer control and high-efficiency (over 98%) boost power converter. This device acts as a variable resistor for the solar panel, tracking the maximum power point for the current light intensity, and as a battery charger for the battery bank. Since MPPT's use a boost converter, the solar panel voltage should never exceed the battery bank voltage. In fact, most manufacturers recommend that the solar panel nominal voltage should be at least 5% lesser than the battery voltage. This restricts the connection of the solar cells in the panel and sets a range for the nominal voltage of the main panel.

Other problem occurs when connecting deploying the telescopic panel. In order to avoid using additional DC-DC converters, this panel should be rated at the same voltage as the roof panel and connected in parallel with it as shown in Fig. 3.

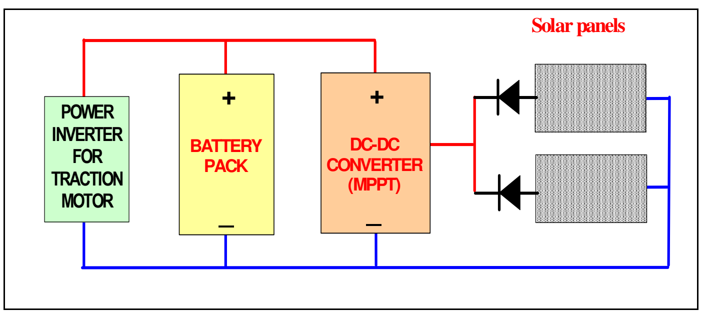

Fig.3. Electric diagram of the solar EV

There is an additional problem: when a solar cell is shaded, its maximum current is limited [4]. If the shaded cell is connected in series with other cells in a panel, the partial or total shadow on it limits the current of the entire panel. This situation may destroy the shaded cell. To overcome the problem, the shaded cell should be disconnected or bypassed. With this objective, the panel is divided in several blocks of solar cells, and each block has a bypass diode connected to its terminals. When a solar cell is shaded, the entire block of the cell is automatically disconnected and the rest of the panel can operate normally, reducing the negative effects of shading.

Energy optimization would not be complete without the use of regenerative brakes and ultracapacitors. A regenerative brake system is able to convert kinetic energy in electricity, and an ultracapacitor bank acts as a high power source or sink, improving the vehicle performance and the battery bank life.

B. Mechanical Design Issues

Substantial improvements in the EV performance can be achieved by reducing mechanical losses. It is important to reduce rolling resistance by using high-quality bearings and low-coefficient tires. For high speed operation, is even more important to reduce aerodynamic coefficient. Solar panels should be set in order to keep the aerodynamic coefficient low. It is also important to create an aerodynamic structure with a rear slope that produces vortices over the main solar panel. Vortices would increase heat interchange and then cool the solar cells, improving their efficiency.

Finally, if the mechanical design of the vehicle is adequate, it would be possible to add even more solar panels in the rear and sides, caring for not obstructing visibility. These panels , fixed with a hinge system to the main panel, could also be deployed when parked, in order to increase the collecting surface, and thus lowering the battery pack charge time.

IV. Potential of this Idea

The concept of commuter-oriented EV represents a particular case of a standard EV. Although commuter-oriented EVs should be more restricted than standard EVs, important improvements in performance could be reached when operated under certain conditions. In order to maximize the vehicle performance, these conditions must be optimal.

With this aim, a sunny, predictable environment with high insolation levels over the year must be chosen. To agree with this, the region must be preferably a desert near equator with low probabilities of clouds. Located in Chile, Atacama Desert is the most arid place in the world (Fig. 4). It almost never rains there, and skies are clear during 98% of the year. Its location (latitude 22^o – 24^o South) ensures long days during the entire year. Although high temperatures reduce solar cells performance, high insolation levels compensate this negative effect.

Fig. 4. Atacama Desert Location in the North of Chile

Table 1 shows the Atacama Desert insolation during clear sky days in a 10 year average ($kWh/m^2/day$):

Table 1

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
8.74	8.77	7.62	6.41	5.43	4.68	4.93	5.98	7.05	7.96	8.64	9.08

It is important to choose a city where buildings are small, in order to reduce shading. Cities such as Calama, or villages such as San Pedro de Atacama are suitable for these purposes. In Atacama Desert, there are lots of villages around main mining companies. Workers live in company-owned condominiums. If those companies adopted a transportation system like the one presented in this work, they could design their condominiums (small buildings, charging systems in parking lots, etc.) in order to maximize the efficiency of small-size EVs. Under these controlled conditions, the benefits of this city-oriented vehicle concept are evident.

V. Conclusions

The feasibility of improving performance of a battery powered commuter-oriented electric car, using photovoltaic cells, has been presented. The work shows that small EVs with solar collectors, used in special sunny places like the cities in the North of Chile, can increase the range in more than 25 %. This figure is easily reached if some additional considerations such as improvements in weight, battery capacity, mechanical structure and accessories are taken in account. All these considerations will be taken in account for the construction of a prototype in our "Electric Vehicles Laboratory" at the Pontificia Universidad Católica de Chile.

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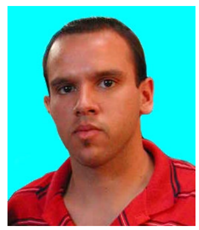

Daniel Soto received its title of Civil Electrical Engineer in October of 2002. Presently, he is applying to the European Master Program in Renewable Energy.