Off-Grid, Low-Cost, Electrical Sun-Car System for Developing Countries

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***Abstract*—Fully electric cars are now available. This technology offers exciting opportunities, especially to citizens of developing countries in equatorial regions having high concentrations of solar energy. The major motivation behind adoption of electric vehicles is reduced CO_2 output. However, most electric vehicle batteries are charged by electrical grids powered by coal and oil, which themselves produce significant amounts of CO_2. Charging electric vehicles with solar energy can dramatically reduce CO_2 generation. The authors have demonstrated a low-cost electric vehicle charging station using 4 solar panels of 255 watts each, batteries, a charge controller, and an inverter. For 3 months, a SMART Electric Drive automobile was successfully charged using only solar energy. The proposed "Sun-Car System" presents a low-cost opportunity for poorer populations such as those found on Indian reservations in the southwestern United States and tribal Africa. Community-owned electric vehicles could be charged solely with solar power. The demonstrated off-grid solar charging system is relatively low-cost, and would not require an electrical grid or an expensive gasoline/diesel delivery infrastructure.**

Keywords: — solar; electric vehicle; battery charging; solar power.

I. Introduction

A. Motivation

According to the MIT Technology Review, 1.5 billion people on this Earth currently lack electricity, and this in the 21st century [1]. Nearly seventy percent of the population of sub-Saharan Africa, approximately 600 million people, is without electrical power [2]. Many people on Indian reservations in the United States also lack access to electricity.

While such communities can have shared vehicles, these must often be driven to far away locations in order to be refueled, and additional costs are incurred with each refueling.

The emergence of commercially available electric vehicles and reduced costs of solar panels and wind turbines offers solutions to both of these problems, especially in regions rich in solar energy, where electric vehicles or plug-in hybrids can be charged using an off-grid, low-cost solar charging station. Such a simplified transportation system does not require fuel to be obtained or delivered from far-away places, and does not incur additional fuel costs once installed. If the vehicle and charging station are obtained by federal grant or through a charitable organization, the costs to the community are minimal.

B. Background

In developed nations, the electric car is often viewed as an adult toy – a novelty rather than a necessity. In underdeveloped regions, on the other hand, a low-cost transportation system based on solar or wind energy could significantly impact the entire economy.

At the end of 2013, about 36 GW (peak) of solar photovoltaic (PV) systems were installed in Germany. This corresponds to about 150 million solar panels. Due to limited sunlight and low solar panel efficiency, one megawatt of installed solar power in Central Europe collects approximately one gigawatt-hour of electricity annually.

While the "global annual horizontal irradiation" in Germany is about 1000 kilowatt-hours per square meter, it is 2.5 times higher in most areas of Africa – about 2500 kWh/m^2 [16]. In addition, the shadow cast by a solar panel supplies some shade, and therefore "cooling power". While this is not needed, or even desired, in northern countries, the added feature of shadow generation is welcome in the deserts of Southwestern USA or in Africa. Assuming the cooling effect of the shadow produced by the solar panel is between 500 and 1000 kWh/m^2, a solar panel installed in Africa is then 3 to 3.5 times more effective than in Central Europe.

This solar panel cooling effect can also be critical to the adoption of electric vehicles in very warm areas, since the lifetime and efficiency of lithium-ion batteries are negatively affected by heat. Parking electric vehicles under solar charging panels can extend the lifetime and performance of electric vehicles in underdeveloped nations, thereby reducing overall costs.

II. Electric Vehicles

A. Advantages

More and more plug-in electric (hybrid and non-hybrid) cars are coming to the market. Currently, these include the 2-seat SMART Electric Drive, the Ford Focus Electric, the Chevy Volt, the VW E-Golf, the Nissan Leaf, the BMW i3, the Opel Ampera, the Toyota Plug-in Hybrid, the Tesla, the Honda Civic Hybrid, and others. Most of these cars are charged by the electric grid. However, replacing gasoline with electricity from a national grid does not necessarily lead to a significant reduction in carbon footprint since, in the USA at least, more than half of the nation's grid power still comes from coal, oil, and natural gas.

A main advantage of an electric motor is its higher efficiency compared to a combustion engine. Let's look at the fuel costs. The EPA/DOT fuel economy for the Smart Electric Drive (according to the data sheet) is 107 MPGe, or 32 kWh per 100 miles. MPGe means "miles per gallon of gasoline equivalent" and is used by the "...U.S. Environmental Protection Agency to compare energy consumption of alternative fuel vehicles, plug-in electric vehicles, and other advanced technology vehicles with the fuel economy of conventional internal combustion vehicles expressed as miles per U.S. gallon" [3]. Since a gallon of gasoline contains approximately 33.7 kWh of energy [4], the following numbers are obtained for the SMART car:

- SMART-for-Two, 2008, Gasoline Engine: 38 miles per gallon, or $0.10 per mile (assuming a fuel cost of $3.80 per gallon);
- SMART ED (Electric Drive), Grid-Tied: 107 MPGe; 0.32 kWh per mile, or ~$0.05 per mile (assuming a cost of electricity of $0.16 per kWh);
- SMART ED, Sun-Car, Off-Grid, after pay-off of charging station: $0.00 per mile

The gasoline engine produces about 8.9 kg (19.6 lbs) of CO_2 for every gallon of gasoline, or every 38 miles of driving. Thus, about half a pound of CO_2 is produced for every mile driven. This is reduced to 0 pounds per mile if an electric vehicle is powered by solar energy. In this case, CO_2 emissions are reduced by about 25,000 pounds (more than 11 metric tons) for every 50,000 miles driven.

Other advantages of electric vehicles include their more simple construction compared to gas-powered cars, (*e.g.*, oil changes are not necessary), and features such as regenerative braking, which leads to a further increase in efficiency.

B. Challenges

The main problems of electric vehicles are the limited charge content (miles per charge) and the high price of their batteries. A great deal of research is going on worldwide to improve both parameters.

Most electric cars have lithium ion batteries that may experience temperature-related problems or failures in very hot areas such as Arizona or Africa. Clever cooling solutions will no doubt be developed in time. Further, several advances and improvements in battery technology are on the horizon. Some of these are discussed by K. Bullis in MIT Technology Review [5, 6]. For example, nanostructures are eventually projected to lead to a five-fold increase in battery life [6]. These improvements are, however, several years out.

Challenges are also introduced by battery charging procedures. There are basically two technologies: Conductive charging, which is used in most cases [7], and dynamic wireless charging [5]. In general, there exist three systems that yield different charging times:

- Level 1 charging: 120 VAC, 60 Hz.
- Level 2 charging: 240 VAC, 60 Hz.
- Level 3 charging: 400 VDC, 0 Hz.

Certainly, as pointed out by Zehner [9], the ability of electric vehicles to reduce greenhouse gas emissions is often overstated, especially in northern industrialized nations, where the available solar energy is limited. In hot, equatorial regions, however, solar panels are much more effective and collect more energy, making this a different case entirely. In these areas, the environmental manufacturing costs associated with electric vehicles, lithium-ion batteries, and solar panels are quickly negated.

Moreover, better and lower-cost solar cells can be expected in the future. A Boston-based company, 1366 Technologies, claims they can make solar cells at less than half the cost of current cells [10]. Their starting material is molten, fluid silicon.

C. North and South

While it may be obvious, one of the reasons why industrial nations are located in northern regions is simply because it is easier to work in cooler climates. Many underdeveloped nations are located in southern or equatorial and large desert areas. These locations receive the most solar energy.

Living conditions in parts of Africa would appall many. For example, in an eastern African country close to the Equator, there is a village with about 700-800 inhabitants living in about 250 grass covered huts. The latter have no flowing water and no electricity. There are no railway or ship connections, no gasoline cars, no taxi or bus services, no gas stations, no electrical grid, *etc*. Similar situations can be found in many southern developing countries [11].

The introduction of a few electric cars operated with off-grid solar energy could become a real game-changer with relatively little investment capital. The cost of the off-grid charging station can be a fraction of the price of an electric vehicle, maybe 10-15%. Community-shared electric vehicles could provide transportation for an area inside a 60-100 mile radius. No expensive infrastructure (gasoline pump stations, tankers, *etc.*) is necessary. Organizations such as Power Africa or the U.S. Africa Development Foundation (ADF) could donate a few electric cars. This system would also fit nicely into the ADF's so-called "Off-Grid Energy Challenge" [12].

The status of solar energy use in Africa is described by the following headline: "Uganda slow at seizing solar energy opportunity amid high energy costs" [13]. However, help is on the way. For example, the U.S. government plans to spend $7 billion to electrify sub-Saharan Africa in the next 5 years [14].

III. Proposed Solution

The implementation of conventional transportation systems requires a lot of capital that developing countries generally do not have. Even in industrial nations such as the U.S., most consumers still opt for gasoline-powered vehicles. This is due in part to the higher cost of electric vehicles and their relative novelty, which leads to the sense that electric vehicles are still somewhat unproven and risky. This sentiment is borne by the facts: In 2013, 15.5 million cars were sold in the U.S., but only 96,552 of these were primarily electric vehicles [15]. However, due to the abundance of solar energy in hot areas, the combination of electric cars and off-grid operated solar charging stations could provide an almost ideal solution to the existing transportation problem in these areas. Compared to conventional on-grid charging, this system has the advantage of reducing the carbon footprint to almost zero once installed.

A. The "Sun-Car Kit"

MTECH Laboratories has developed and tested a low-cost, off-grid, easy-to-install solar charging station prototype called the "Sun-Car Kit". A simplified block diagram is shown in Fig. 1 and a photograph of the initial assembly in Fig. 2. Four 255-watt (peak power) solar panels (1020 W_{pk}) from Solar World were used. This unit can be used at any workplace or close to the home if space is available.

The solar panels can either be mounted on the ground as shown in Fig. 2, or on a scaffold-like structure under which the electric vehicle could be parked during charging, as shown in Fig. 3. This also serves to protect the car and its batteries from the sun and to keep them cool. Excess solar energy, for example when the car is not being charged, is stored in a battery bank.

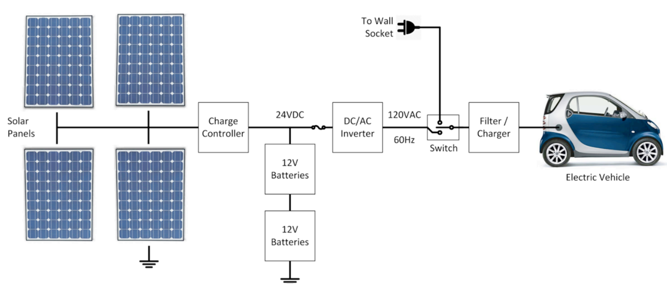

Fig. 1. Simplified block diagram of the proposed solar charging station for electric vehicles.

Fig. 2. Working prototype solar electric vehicle charging station set up at MTECH's facilities in Ballston Spa, NY.

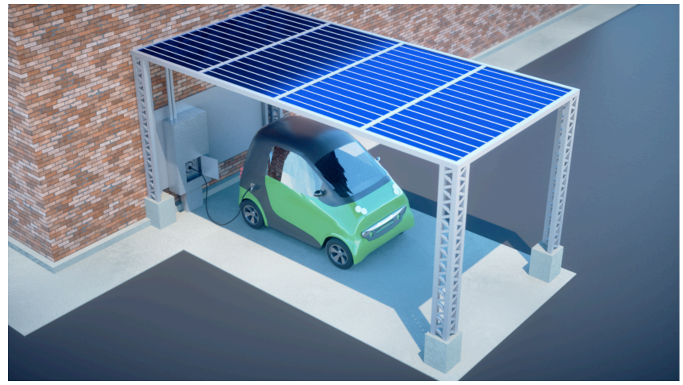

Fig. 3. Artist's rendering of one style of solar charging station proposed.

In this prototype, 4-6 deep-cycle marine batteries (type 27) were used. The batteries also provide excess power while charging the SMART car with about 900 W. A charge controller is inserted between the solar panels and the batteries in order to protect the latter. The 24-VDC system feeds a 2-kW pure sinewave inverter that provides 120 VAC at 60 Hz.

For a three-month period, a SMART Electric Drive vehicle (model "For-Two") was charged strictly from the prototype solar charging station, without any power delivered by the grid. Depending on the Upstate New York weather and cloud cover between August and November (2013), 1-4 kWh could be collected each day. One kWh translates into about 3.2 miles of operation. More solar panels could, if necessary, be added. The system could also be combined with wind turbines to further enhance energy generation.

Workplace charging stations benefit from the fact that they collect solar energy 8-12 hours per day, even when cloudy. Until power grids are energized by completely renewable energy sources, the proposed off-grid charging system provides an attractive solution to the powering of electric cars as far as carbon footprint reduction and costs are concerned.

IV. COSTS

The cost of one kilowatt (installed power) obtained from the sun has dropped more than 100 times from \$76,670/kW in 1977 to about \$740/kW in 2013 [18]. Assuming this power is available for 8 hours of the day on average, a 1-kW solar array should yield around 8 kWh per day – about 25 miles per day or just over 9,300 miles per year for the SMART Electric Drive (3.2 miles/kWh). Using Uganda as an example with its fuel cost of \$5.40/gallon [19], the equivalent annual gasoline cost at 38 mpg is around \$1325. Assuming the complete charging station (including storage batteries, solar panels, inverter, and so on) can be purchased for under \$3,000, the solar charging station could pay for itself in about two years. In the third year and beyond, fuel costs would be zero.

The cost of solar panels will certainly continue to drop. In addition, there is a worldwide effort to reduce the cost of lithium-ion battery technology, which will lead to the availability of lower-priced electric vehicles in the near future. On the other hand, the economic benefits of giving remote populations a means of traveling to nearby cities should be considerable.

V. OTHER CONSIDERATIONS: THE "2/5 SYSTEM"

A vast amount of energy is unnecessarily wasted every day. According to the US Bureau of Transit Statistics, there were around 251 million registered passenger vehicles in the United States in 2006. Of these, about 99 million were SUVs and trucks. Yet almost all of these 251 million cars are designed for transporting 5 to 7 passengers and therefore weigh about 3 to 4 thousand pounds. The average American family owns two such cars. This arrangement can be called the "5/5 System." But most people never consider the fact that the vast majority of all trips (estimated at 98% to 99%) are made with only one or two passengers. Thus, hundreds of millions of miles are driven each day by only one or two people (100-400 lbs of "cargo") in automobiles designed for 5 to 7 people (3,000-4,000 lbs of vehicle).

The 2-seat SMART "Sun-Car-Kit" supports the so-called "2/5 System". The idea is simple: Instead of owning two heavy and inefficient cars designed to carry an entire family, the average family would own one conventional 5- to 7-seat car and one small and fuel-efficient two-seat car weighing half as much (hence the term "2/5 System"). The small car would be used for daily commutes and the larger one for family excursions. This will drastically reduce the fuel consumption for personal transportation (by as much as an estimated 30%-50%). Based on their size and weight, smaller plug-in electric vehicles, in theory, require less charge to run a given number of miles, especially in suburban or urban settings. Thus, the solar charging station will provide greater mileage to smaller cars, especially 2-seaters such as the SMART Electric Drive. The availability of this 2-seat electric car (and others are sure to follow) enables the 2/5 System.

VI. SUMMARY AND CONCLUSIONS

In 2013, the U.S. populace bought 160 times more gasoline/diesel cars than electric cars [15]. This will no doubt change dramatically as electric cars become more ubiquitous, are proven through long periods of ownership and use, and are improved in both cost and performance. The range limitation will also become less of a factor as battery performance is enhanced. This opens the door to off-grid charging stations.

MTECH's "Sun-Car Kit" is a low-cost, easy-to-install, off-grid solar charging station for electric vehicles, which can be easily expanded by simply adding more solar panels. Significant savings in fuel and/or electricity costs and a reduction of CO_2 emissions are possible. The system is especially well-suited for work-place commuting, wherein electric vehicles could be charged by an on-site, off-grid charging station during working hours, yielding enough charge for the drive home.

Because of its low cost and simplicity, the demonstrated Sun-Car Kit could provide a tremendous opportunity for all hot areas with underdeveloped or non-existent personal transportation systems. Even in developed nations, farms and rural areas could benefit from the technology.

The solar electric vehicle charging station is also an excellent teaching tool for high-school and college students, who need to understand the concepts of volts, amperes, watts, kilowatt-hours, miles per gallon, MPGe, and the intricacies of solar collectors, charge controllers, batteries, kilowatt inverters, and of energy and transportation systems in general.

This idea is certainly not new. Solar charging stations for electric vehicles already exist in places such as New Mexico and Arizona, Mississippi, and even Maine [20-22]. However, the concept is especially promising in developing nations and areas. The introduction in these regions can have a profound effect in raising the quality of life for vast populations around the world, which, in turn, will bring new educational and economic possibilities to millions. This can only benefit the world as a whole.

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