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Analysis of energy capture by vehicle solar roofs in conjunction with workplace plug-in charging

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Abstract

Solar cells integrated into electric vehicles have long been a mainstay of collegiate racing competitions, but the small amount of roof area has prevented vehicle-solar installations from having a dramatic market in more conventional vehicles. Still, vehicle solar roof installations have a great potential because they can almost always be exposed to the sunlight as they are frequently parked for hours in parking lots at work, shopping, or other open spaces. At the same time hybrid and electric vehicle drivers are typically concerned about their all-electric driving range and do whatever they can to plug-in and "top off" the battery whenever possible. Unfortunately this behavior mode of topping off the battery can establish situations where the vehicle's solar collection is neutralized because the battery is already full. This paper analyzes this conflict for different charging and driving scenarios with an emphasis on commuters who would have access to workplace charging. It is found that regular commuters who make use of level-2 workplace charging could experience a loss of more than 75% of the potentially available photovoltaic output from roof-installed solar on their vehicles. This surprise finding is discussed from the perspective of plug usage habits and "range anxiety".

Keywords: Solar-on-vehicles; Plug-in electric vehicle charging; Solar array energy maximization; Green commuter transit

1. Introduction

Much is known about the use of photovoltaic (PV) arrays for generating electrical power. Semiconductor devices, usually silicon-based, are excited by certain wavelengths of light and the output power scales roughly linearly with the intensity of light shining on the panels. Peak power point trackers are able to adjust the operating voltage of the PV devices to achieve a maximum output with respect to the available sunlight irradiation (Esram and Chapman, 2007; Koutroulis et al., 2001). Based on these peak output rates, the US Department of Energy (DOE) has provided web-based tools to allow projections of PV array output as a function of all the critical parameters including geographic location, installation tilt, tracking ability and other parameters giving monthly or annual output projections (Marion et al., 2001). Most users are interested in annual averages, which are then related to predictions of pay-back periods based on the electricity value compared to array installation cost. This average analysis is based on the utilization of grid-connected solar arrays that are always able to collect the sunlight that is available and even feed it back to the grid when local usage is lower than the power that is being generated, meaning that none of the available sunlight is wasted; grid-connect PV arrays are typically always "on". Connecting this green source of electricity with plug-in vehicles is an obvious next step that can provide transportation with nearly zero green-house

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gas (GHG) impact. Significant work has already been directed at matching PV generated power with electric vehicles (EV), though typically the PV is not directly installed on the vehicles in question (Birnie, 2009; De Schepper et al., 2015; Denholm et al., 2013; Benela and Jamuna, 2013; Chen et al., 2014; Chukwu and Mahajan, 2014; Liu et al., 2015; Pantos, 2011; Saber and Venayagamoorthy, 2011; Shi et al., 2012; Tarroja et al., 2014; Traube et al., 2013; Tulpule et al., 2013; van der Kam and van Sark, 2015; Zhang et al., 2012; Zhang et al., 2015; Redpath et al., 2011), though the energy value is maintained.

A vehicle-roof-installed solar array, however, is *not* grid-tied and will only be operational in situations where the vehicle's battery has room to accept the energy being collected by the array. Thus, the driving and plug-in habits of the vehicle user can significantly influence the solar energy capture[1]. And, for commuters driving to and from work on a regular basis, the particular times of departure and arrival will influence the battery state-of-charge (SOC) and will thus influence the net yield of energy for that vehicle/solar installation. A few studies have examined solar charging of vehicle batteries including the natural rise in battery voltage as the SOC changes, depending on the battery chemistry, solar array size, and peak-power point tracking method(Gibson and Kelly, 2010; Kelly and Gibson, 2011; Kelly, 2012; Nguyen et al., 2013). But, so far there has not been analysis of the impact of the "full battery" condition on the solar energy yield for such systems.

To compound matters further, the seasonal variability of dawn and dusk times can also be important in relation to the particular driving habits for any specific commuter. To compare these effects we have accessed the more detailed information that can be found in the DOE's Typical Meteorological Year database (TMY3) Wilcox and Marion, 2008. These data are required for the present analysis because we consider how hour-by-hour sunlight brightness and length-of-day variations will define limits on the available sunlight and thus influence the ability of a vehicle solar array to provide energy for propulsion.

To illustrate the dramatic range of daily and seasonal sunlight variations, Fig. 1 gives the daily integrated sunlight exposure throughout a full year for Newark, New Jersey, as an example location[2]. In this case the "global horizontal irradiance" (GHI) was used as the best representation because a solar panel on a vehicle would likely be nearly level with the ground (knowing that the vehicle would need to drive in all directions). The large swing from winter to summer is quite obvious and well understood. The large day-to-day variability is due to clouds and storms that sometimes cut down on the sunlight brightness, but perhaps only for a short time. Every geographic location has its own variability characteristics.

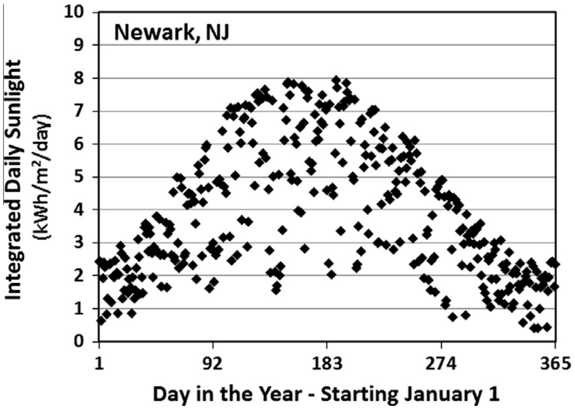

Fig. 1. Daily integrated sunlight irradiation throughout the year based on data from NREL's Typical Meteorological Year Database for Newark, New Jersey.

Given this sunlight availability, it is relatively easy to estimate the additional electric driving range that a hybrid or electric vehicle might achieve if this sunlight were to be efficiently converted to electricity. The global annual average insolation for the NJ location is just below 4 kW h/m^2/day. But since the standard testing condition (STC) for solar modules makes use of solar-spectrum-equivalent light having 1 kW/m^2 brightness this then integrates to an effective ~4 h of DC output scaled to the array's "name-plate rating" during an average day. This gets down-rated based on slight inefficiency for inverters and other factors that might still allow 85–95% of this energy being delivered as AC output to the grid (or converted to the DC voltage-of-choice for the vehicle's battery/power system).

Now, again considering a vehicle-roof solar installation it must be understood that the possible area covered by solar panels is realistically quite small. Though collegiate racing teams design their vehicles to increase the array size (providing between 1000 and 2000 Watts-peak, W_p, output (Suarez-Castaneda et al., 2014; Sullivan and Powers, 1993), mainstream production vehicles have much smaller roofs and proportionately lower solar collection potential (Giannouli and Yianoulis, 2012). For example the recent Ford roof-installed-solar concept car (the "C-Max Solar Energy Hybrid") has around 300–350 W_p output from an array covering only about 1.6 square meters of roof (Ford C-Max Solar Energi Concept Car, 2014). Other prototype and experimental vehicles with solar roofs have delivered lower peak powers: two variants with 215 W_p

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[1] The topic of driving and plug-in habits is known to include aspects of parking location choice that might influence the solar exposure. For example regular vehicle drivers typically prefer garage or shaded locations to reduce weathering of paint and vehicle interior. The present analysis is built on the assumption that drivers of the PV-enabled vehicles would choose to modify their parking habits to find more open locations when possible. This will be further complicated by the locations where EV plug-in infrastructure may have been installed and whether they might be shaded. Thus, the present analysis has to be considered a "best-case" where full exposure during driving and parking can be reasonably maintained.

[2] The integration has been performed using the TMY3 hourly irradiance intensities and assuming PV module output scales linearly with intensity.