

Improving Energy Yield for EV-Mounted Solar

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Summary

Solar arrays on vehicle roofs provide only rather modest amounts of cumulative energy output; thus vehicle designers cannot depend on them for major traction power. However, the trickle charging *can* provide a useful amount of energy and offset the use of grid-supplied electricity and improve the carbon footprint of EV transit. This paper examines the energy congestion effect when the roof-top solar is used to supply the main traction battery. Regular commuters who have access to work place charging may experience substantial reduction in energy capture because of the speed of grid charging. Strategies for improving energy yield are presented.

Keywords: EV, Photovoltaic, Optimization, Energy Storage, Range

1 Introduction

Solar cells integrated into electric vehicles are familiar sights as featured in collegiate racing competitions [1,2] and also have been used to give more conventional electric vehicles an extra edge and appearance of environmental benefit [3,4]. However, the real energy output from these arrays is relatively low partly because most normal vehicle roofs are relatively small. Still, vehicle solar roof installations have interesting 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 frequent situations where the vehicle’s solar collection is neutralized because the battery is already full. This paper analyzes this conflict with an emphasis on commuters who would have access to workplace charging. Fig. 1 highlights this basic conflict.



Figure 1: Roof-installed PV panels provide slow trickle charging compared with the much faster grid-sourced power. If these both feed the same battery then the grid-charging may effectively negate future solar generation later in the day.

While the conflict for battery space is real, it provides an opportunity where careful planning and smart controller logistics can be designed to improve the total energy capture. In the simplest terms the controllers must reserve some of the main battery’s capacity for anticipated solar energy generated during the next few hours of daylight while parked. Below we examine the hour-by-hour sunlight variation for one east-coast US location and show how the relatively good predictability can suggest a method for operating this

EV+PV configuration to achieve very close to ideal solar array energy capture. Finally, the trade-off between vehicle range and solar energy capture efficiency is discussed.

2 Background

Connecting photovoltaic electricity with plug-in vehicles is an obvious linkage that can provide transportation with nearly zero green-house gas (GHG) impact. Significant work has already been directed to matching PV generated power with electric vehicles (EV), though typically the PV is not directly installed on the vehicles in question [5-7], though the energy value is preserved by connection to the grid. A vehicle-roof-installed solar module, 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. Recently, we have tested a model of the energy yield for cases with and without workplace EV charging and that compared Level-1 versus Level-2 charging [8]. The energy yield was found to be reduced by as much as 75% for the case of Level-2 charging at work (which is the presently most predominant option in the US). The present paper examines a method for preventing that solar energy collection loss. First, the basic model of analysis is described, followed by a short discussion of further methods for improving the solar capture yield.

3 Model

The solar array performance model is based on an installation where the main traction battery is shared by the two inputs and where the battery controller will shut down both grid and solar charging when the battery is full (as it should). A simple driving pattern was chosen: that of a daily commuter. Fig. 2 shows an overlay between the driving pattern and the available sunlight for a randomly chosen day (using data from DOE's Typical Meteorological Year 3 database [9] for Newark NJ).

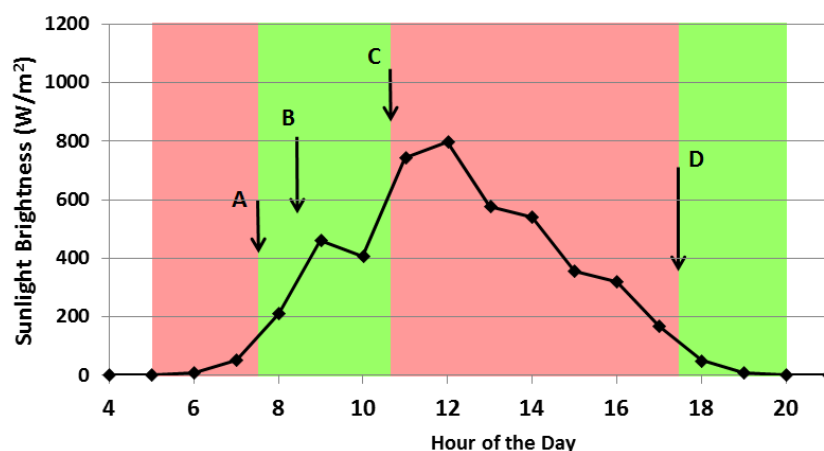


Figure 2: Energy capture effectiveness for a randomly chosen day showing sunlight variations. A-D notations and background color shading are explained in the text.

The sunlight intensity is plotted as a function of time for a randomly chosen day (TMY3 has full-year datasets with hourly interval resolution). Different time spans are shaded green or red to highlight times when the solar electricity can or cannot be captured based on the battery SOC, respectively. For the early morning (up to point A) the car is parked and the battery is full, having been filled during the night before and therefore a little bit of morning sunlight is not captured, up until the point when the driver starts their commute (here selected to be 7:30 AM). During the full duration of the commute the power use by the vehicle is larger than the power generated by the array so all the solar power can be collected effectively and reduces the additional drain from the battery to provide the driving need (from time A to time B). Upon reaching work the driver plugs in immediately and for some time afterward the battery will be receiving grid power; simultaneously, solar power will also be collected (from time B to time C). Time C indicates the point when the battery reaches 100% capacity and no more grid or solar power will be received; the solar array becomes deactivated at this point. Only when the driver leaves work for the evening commute (point D, here drawn as 5:30PM) does the solar array become operational again. When the driver reaches home they may plug in right away, but the battery will have capacity to accept solar for all the time required to fill the battery again, until sundown when only grid power will be available. A nominal one-way commuting distance of 15 miles was selected as the basis for the comparison, which

covers a majority of daily commuters coming to the author’s campus location [10]. Average commuting speed and energy usage during rush-hour travel times were based on historical commuting data accumulated while driving a 2012 model year Chevy Volt [11]. It is clear from Fig. 2 that a substantial part of the day’s sunlight is falling on the array at times when the battery is already full (zones highlighted in red). This may seem surprising, but derives from the relatively small PV output capacity compared with the rate of grin input at level 2.

4 Baseline without Battery Usage Planning

The commuter driving habit described above was applied to all 365 days of data for Newark NJ, a location close to the author’s university. Fig. 3 shows the day-by-day solar yield penalty caused by the full-battery condition.

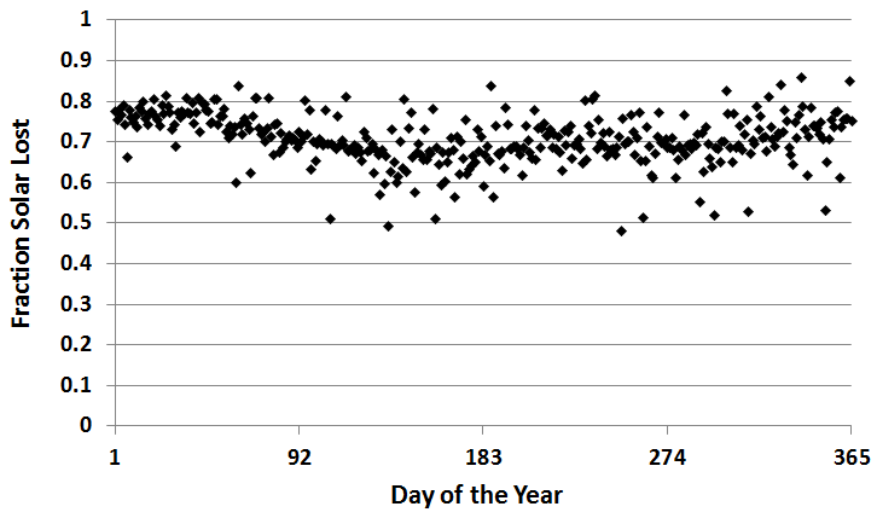


Figure 3: Energy capture effectiveness for a full year for the TMY3 data for Newark NJ.

The differences throughout the year are not substantially seasonal, though naturally there is much more available solar energy during the summer months. Still, the *fraction* of available energy lost is quite high throughout the year. Fig. 3 simply illustrates that using work place plug-in charging as a commuter does an excellent job of filling the battery relatively early in the day – and shutting off the solar panel for much of the afternoon. The scatter seen is representative of occasional conditions where morning and afternoon weather conditions yield markedly different sunlight brightness levels. Other plug-in and driving habits result in different energy yields, as discussed further in reference [8].

5 Preserving Battery Capacity for Future Solar Input

The critical idea presented here is that once the traction battery is nearly full then it would be possible to curtail charging and preserve the last bit of battery space for future solar input that will likely arrive during the later parts of that day. Referring back to Fig. 2 this would be tantamount to stopping grid charging somewhat before time “C” and then having enough battery capacity still remaining that the future solar input can be captured effectively (the full time range from then up until time “D”). Clearly, the battery management system needs to make this decision before time “C”, which is before we know what the later solar output will be. So, accurate predictability of future sunlight brightness is critical. There may also be a need to predict when the driver might be expected to unplug (time “D”), etc.

Again, working with NREL’s TMY3 database [9] we can test one simple model for predicting future sunlight brightness, which can be used to predict the electric energy output that might likely be gathered by the vehicle’s solar panel after time “t”. Since we don’t know exactly when the battery might get full (time “C” above), then we need to develop a correlation that would not be limited to the hour-by-hour intervals in the TMY3 database. To achieve this fit we work with the hourly data and make an algebraic fit for the data to reach a workable predictive function. Fig. 4 (next page) shows the first step of this operation – illustrating the predictability evaluated at 10:00 AM in the morning. We take the TMY3 data and sum the solar irradiance up to 10:00 AM and likewise sum the solar irradiance summed for all hours *after* 10:00

AM, which are drawn from historical data collected at the specified location. These are plotted as the X and Y axis values, respectively, yielding the plot here:

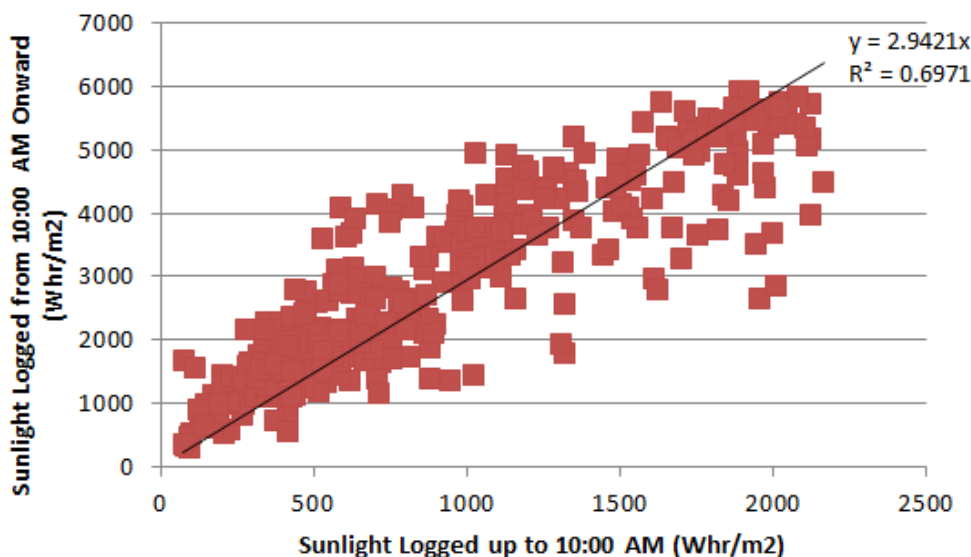


Figure 4: Correlation between early and late cumulative sunlight irradiance based on a cutoff time of 10:00 AM. Working from the known history up to 10:00 AM then it is possible to project what the remainder of the day's solar output will likely be.

It comes as no surprise that if the morning is particularly sunny it will be likely that the remainder of the day will also be sunnier than average; or, if a storm is raging in the morning then the afternoon outlook will be less optimistic for future solar energy generation. Obviously, there is some scatter in this plot, but the general trend is still quite strong and the predictability using this correlation is good. For the present purposes it is enough to represent this correlation as a line that passes through the origin. And, the same correlation can be extracted for cut-times at every hour interval (the maximum granularity of resolution available in the TMY3 dataset). Fig. 5 shows the slope results for several of the time cut-off points:

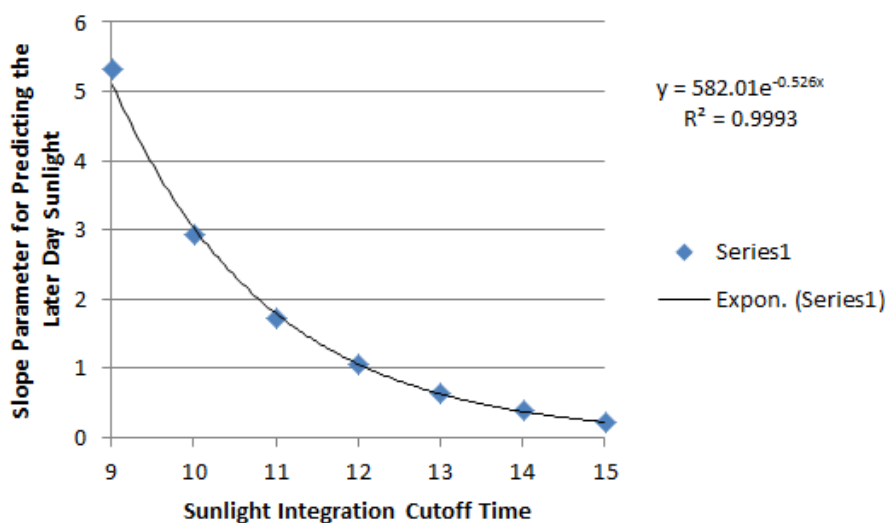


Figure 5: Hour by hour regression slopes for early-vs-late cumulative sunlight irradiance values using the TMY3 data.

Again, it is quite reasonable that the curve is shaped as it is. It has a value very close to 1 right at noon, showing that the morning and afternoon solar brightness values are not that different. Further the data are quite smoothly varying and can be nicely fitted with an exponential curve as labeled. This function can then be used to predict future sunlight for any break point and allow the battery management system to

work backwards and have a good idea about how much battery capacity should be reserved for the remainder of the day and curtail grid charging before the main battery is fully charged.

5 Discussion

It is possible to use these numbers to put some typical vehicle range and solar yield effects together. For example using the 2012 Chevy Volt data [11] (which is an extended range EV) it has been found that a commute of 15 miles would require 4-5 KWH of electric energy, depending on traffic, weather, and driving habits. For level 2 charging this would require something like 90 minutes of active charging. Arriving at work at 8:30 would then result in a full battery by around 10:00 AM. If our EV had been outfitted with a solar array we might expect that its rating would be in the range of 300 Watts-peak (based on a literature survey of customized PV on vehicles in reference [8]). Using that rating and the remainder of the day's sunlight intensity we might expect that approximately 0.9 KWH of energy might still be available for capture (using a Newark NJ average daily insolation of about 4 KWH/m²/day, averaging through the whole year [9]). Since our measured power level when charging the Chevy Volt was around 3KW [11] we would have to curtail grid charging around 20 minutes early so that the right amount of battery capacity would be preserved for that amount of future solar generation. If the grid charging was curtailed to preserve space for the anticipated 0.9 KWH of future solar generation then the vehicle's projected driving range (at the time when the grid charging is curtailed) would be approximately 3-4 miles shorter, out of an approximately 40 mile all-electric driving range for the Volt, amounting to only a 10% range-margin compared to the 75% marginal loss of solar energy if this strategy wasn't used. For battery-electric-vehicles (BEVs) that have larger batteries then the reduction in range and safety marge is proportionately smaller.

The key point is that if the solar array is feeding the traction battery in parallel to grid charging then there will be a fundamental competition between the two [8]. However, by using historical data it is possible to make reasonably accurate predictions of future solar generation, which enables a battery management system to preserve some battery capacity for gradual future use during the rest of the day while the car is parked. It is important to acknowledge that there is an inherent tradeoff between the solar energy captured each day against the vehicle's driving range. In the sense that driving range habits and "range anxiety" are both quite personal and individual characteristics then it is difficult to arrive at a singular optimum for what this solar energy capture method should emphasize. However, it is clear that working from historical data, it is possible to make very practical projections about future sunlight exposure and plan a vehicle's charging accordingly. This prediction model and other variations are subject to a provisional patent application [12]. Related to the development of solar prediction methods, it is also worth noting the recent work at IBM where they have integrated satellite weather forecasting and other data to make highly accurate prediction of future sunlight exposures [13].

6 Conclusion

As noted in the introduction, it is possible to take a more strategic approach to battery capacity management and substantially improve the net yield of the available solar energy resource. At the simplest level this could be done by administratively reserving a certain fraction of the main battery's SOC for use only by the solar array. Our present analysis shows that this battery SOC "reservation" causes only a minor reduction in potential driving range while simultaneously ensuring that most or all of the available daily solar energy can be captured by a vehicle-installed solar array.

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