



## Short communication

## Solar-to-vehicle (S2V) systems for powering commuters of the future

Dunbar P. Birnie III\*

Department of Materials Science and Engineering, Rutgers University, Piscataway, NJ 08854-8065, United States

## ARTICLE INFO

## Article history:

Received 14 August 2008

Accepted 27 September 2008

Available online 17 October 2008

## Keywords:

Solar power

Hybrid electric vehicles

Plug-in hybrids

Commuter vehicles

## ABSTRACT

Hybrid electric vehicles are growing in popularity and significance in our marketplace as gasoline prices continue to rise. Consumers are also increasingly aware of their carbon “footprint” and seek ways of lowering their carbon dioxide output. Plug-in hybrid and electric vehicles appear to be the next wave in helping transition from a gasoline-based transportation infrastructure to an electric-grid-sourced mode, though most plug-in scenarios ultimately rely on having the electric utilities converted from fossil sources to renewable generation in the long run. At present, one of the key advantages of plug-in hybrid/electric vehicles is that they can be charged at home, at night, when lower off-peak rates could apply. The present analysis considers a further advancement: the impact of daytime recharging using solar arrays located at commuters' work sites. This would convert large parking areas into solar recharge stations for commuters. The solar power would be large enough to supply many commuters' needs. The implications for electric car design in relation to commuter range are discussed in detail.

© 2008 Elsevier B.V. All rights reserved.

## 1. Introduction

Recent discussions of climate change have focused on anthropogenic sources of carbon dioxide and the cumulative effect of these emissions that, over time, are expected to have grave impacts on global environment and society in general [1]. In fact, recent shifts toward encouraging ethanol production to offset vehicle fuel needs appear to have contributed to shortages of other grain stocks as farmers shift to corn to meet the ethanol production demands [2,3]. One of the key reasons that ethanol has been pushed so extensively is that more than 25% of our aggregate national energy needs are for transportation [4]—and these needs depend almost completely on fossil fuel sources (much of this imported from overseas). Clearly, finding ways to support our transportation needs without depending so heavily on foreign oil is critical for our political and economic advancement.

One trend that helps ease these constraints is the increasing popularity of hybrid vehicles, with the Toyota Prius being the most successful model having sold over one million worldwide through April of 2008 [5]. Hybrids have two key advantages in their design that help them achieve substantially higher fuel economy: First, since electric motors and internal combustion engines have ideal efficiency at low and high speeds, respectively, they can share the power load and reach an overall higher system energy efficiency. Also, electric motors provide a second functionality—they allow for

“regenerative braking” that then recoups some of the car's motional energy and recharges the battery a bit every time you hit the brakes instead of the normal frictional losses.

As soon as hybrid vehicles became available, hobbyists and electric vehicle enthusiasts were quick to design custom conversions that would allow them to plug-in to grid sources of power [6–11]. And, now mass productions of plug-in commercial versions are in development and are expected to reach the market soon [12–15]. Then during short range driving only electric power can be used—allowing for the beneficial economy of electric motors that incorporate regenerative braking and the lower prices for grid-sourced electricity.

Willett Kempton and others have seized on the plug-in hybrid/electric concept and pointed out an additional advantage: that the batteries in these vehicles can store cheaper night-time power and deliver it back to the grid during daytime hours when demand for electricity is highest [16–18]. Their notion of “vehicle-to-grid (V2G)” connections is appealing but provides only partial abatement of our dependence on fossil fuel since only a fraction of our grid electric generation is from renewable sources. For example, Stephan and Sullivan have examined PHEV use and determined that the CO<sub>2</sub> emission reduction would be around 25% in the short term [19,20]. To the extent that wind or solar can be used to charge the PHEV's then we could achieve the full 100% reduction of CO<sub>2</sub> emissions even compared to the excellent gas mileage that is achieved by hybrid vehicles already. However, if we limit ourselves to night-time charging at home, then solar power is out of the question, though wind generation is clearly viable [17]. On the other hand, the present work advocates situating solar generation capacity where

\* Tel.: +1 732 445 5605; fax: +1 732 445 5595.

E-mail address: [dunbar.birnie@rutgers.edu](mailto:dunbar.birnie@rutgers.edu).

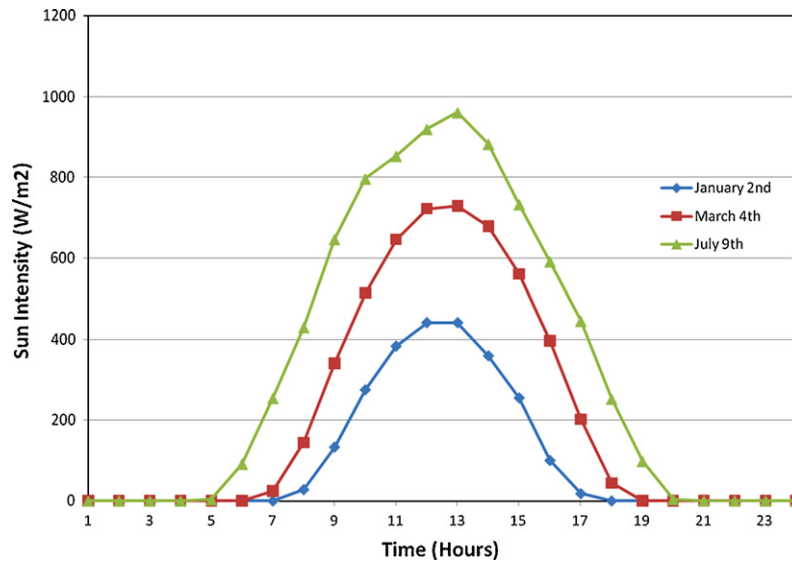


Fig. 1. Hourly integrated sunlight brightness for three selected model days from the most recent Newark Airport Typical Meteorological Year database from NREL.

daytime charging of PHEV's would be especially convenient: in large parking lots where commuters typically leave their vehicles all day long. This concept is developed and analyzed in the next section.

## 2. Concept

Solar arrays installed as shade structures over parking lots used by daily commuters could provide daytime charging of their electric vehicle batteries and reduce our dependence on fossil fuel for transportation and simultaneously help to level generation/demand imbalances that are intrinsic with direct solar-to-grid generation. When evaluating this concept it is useful to compare the energy generating capacity, timing, storage capacity and other practical aspects related to electric, hybrid electric, and plug-in hybrid vehicles that might be used in such systems.

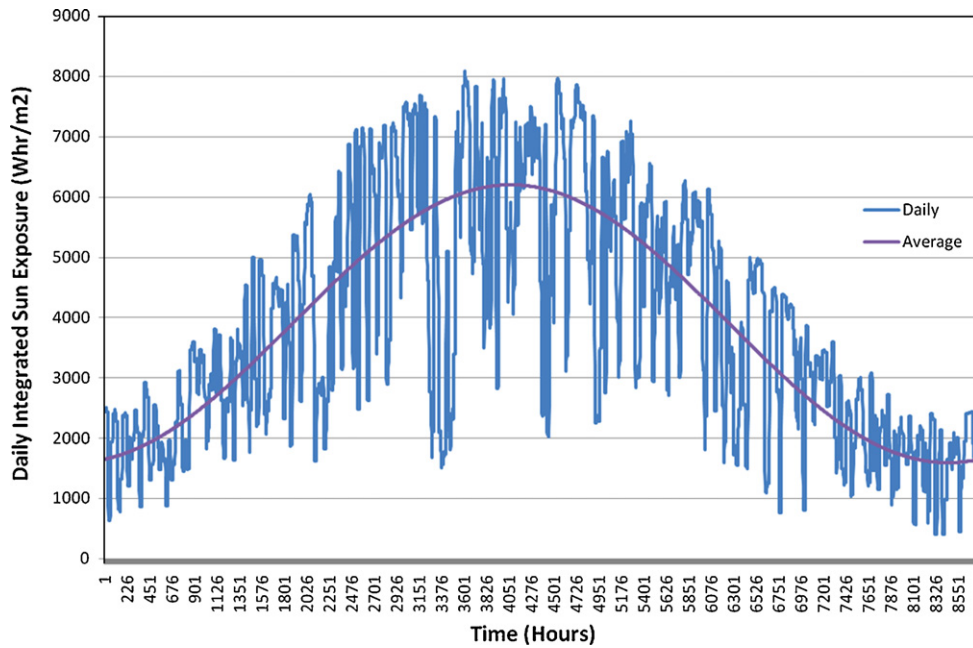
The practicality of such "Solar-to-Vehicle" (S2V) systems will depend on two overlapping factors: (1) the regional solar energy influx and its seasonal variation, and (2) the population density and typical commuter transit distances. For regions where weather patterns or latitude reduce the solar energy influx, it may be difficult to collect enough energy during working hours to satisfy the round-trip energy needs of the commuter. Similarly, depending on the round-trip commuting distance, traffic congestion, and other factors, the energy demand may just be too high. Both factors are examined here, which helps us develop recommendations about PHEV specifications that will optimize this commuter mode.

The National Renewable Energy Laboratory (NREL) has provided data that are useful for analyzing solar collectors in various configurations and locations around the country. Of particular use in the present case is the "Typical Meteorological Year (TMY)" database [21]. Datasets are available for numerous locations around the United States. For general midlevel comparisons it is fair to work with our local New Jersey data and recognize that some areas of the US will be better and some will be worse. Fig. 1 shows lines for three selected, reasonably sunny days of energy flux incident on a horizontal plane (as a function of time throughout each day). This highlights the seasonal variations; average brightness values are about 30% lower, though, when weather variations are considered. The key point from this graph is that, as expected most of the light available for solar capture actually occurs within the peak work-

ing hours of 9 am to 5 pm. The graph also illustrates the increasing number of daylight hours in the summer time for the Newark, NJ latitude ( $40^{\circ}41'45''$ ). Fig. 2 shows a plot of the full seasonal variation including the effects of weather. For estimation purposes, it is reasonable to use average data that show the practical seasonal variation in available sunlight that could be expected. This average line is superimposed.

At this point it is useful to work with these data to estimate what the practical solar collection amounts might be for parking shade structures that could be installed as workplace parking lot collector arrays. Two additional factors are required: the expected efficiency of solar panels and the nominal area for a typical parking space size. Surveying several manufacturers offering larger power modules (in the 200 Wp range) we find expected efficiency values to be in the range of 13–14% [22]. Similarly, parking space geometries are relatively standard with widths of 8–10 ft. being typical and lengths being in the 18–20 ft. range. Converting to metric then we might expect an average parking space to occupy approximately  $15 \text{ m}^2$  area. If this entire area was used for a horizontally situated solar collector then our average daily summertime solar generating capacity would be around  $12,600 \text{ Wh}$  ( $\sim 6000 \text{ Wh m}^{-2} \times 0.14 \times 15 \text{ m}^2$ ), while in the wintertime the average daily generating capacity would be around  $3780 \text{ Wh}$  ( $\sim 1800 \text{ Wh m}^{-2} \times 0.14 \times 15 \text{ m}^2$ ).

These solar generating capacities are interesting when viewed in comparison to the battery pack used in a normal Toyota Prius hybrid. The most recent model is outfitted with a battery pack that is capable of storing 1300 Wh. So, even in the wintertime there is substantially more solar energy available than what the system can store; modification of the system should be envisioned to achieve a longer range and fuller utilization of the available solar power. Even though user modification of the system is not sanctioned by any warrantee from Toyota, there is still quite a bit of information available on the internet that demonstrates Prius conversions to create plug-in hybrids (PHEV's), as noted above [6–11] or a modification that allows the Prius to run in the fully EV mode albeit only at city traffic speeds [23]. Without extending the battery capacity, the Prius is reported to have a range that might be only a couple of miles in electric-only mode. One modification that adds 5000 Wh of battery capacity is reputed to more than double the Prius's gas efficiency and would extend its electric range to 30–40 miles [8]. Even with this extra battery capacity, the average summertime solar power that is available is substantially above what can be stored;



**Fig. 2.** Full year plot of daily integrated sunlight brightness from the most recent Newark Airport “Typical Meteorological Year” database. Scatter is a result of natural cloud and weather variations.

this results in solar power that can be delivered to the grid or used at the worksite. But, in the winter it is possible that the solar energy that is captured may not be enough to fully power a commuter’s energy consumption needs, especially for workers who commute farther.

While the full details of system energy efficiency and achievable EV-only travel range remain to be concretely established, it appears that commuters who live within a 15–20 mile radius of their worksite might be able to become fully solar powered if solar-array parking shade structures were installed at commuter destinations. In fact, US Department of Transportation data show that more than two thirds of commuters travel 15 or fewer miles to reach work and half of the commuters travel 10 or fewer miles one way [24]. Thus with suitable ancillary power storage then daytime charging based on solar collectors of similar size to the car’s parking space could achieve fully zero-carbon-load commuting for most people.

### 3. Discussion

The analysis given above has shown that solar collectors of a size similar to one’s parking space could generate enough power to carry a commuter to and from work using PHEV’s with appropriate battery capacity—at least for commuters within a reasonable distance from the workplace. Such a scenario upends the normal cost/benefit analysis that a home owner might invoke when deciding whether to install solar panels on their house. In the normal case the cost of the solar collection capacity is moderated by a reduction in the electric demand that a home owner would experience. Electricity costs then contribute slowly to pay back the initial cost of installation. Depending on the latitude and prevailing weather conditions, this “pay-back-period” could be many years. Most regions have only encouraged private installations through rebate and tax incentive programs for grid-connected home solar collectors [25]. Now if we consider that a solar collector could be integrated into a parking-lot shade structure and immediately allow for substantial gasoline savings, then a much more rapid pay-back-period could be imagined; this could encourage a more widespread installation of solar capacity. And, the connection to a large automobile-based commuter

population would allow for substantial reduction in green-house gas emissions.

It should also be noted that large workplace parking lots are often relatively open territory where little shade currently exists; solar collectors could be installed without requiring the removal of numerous trees or other obstructions. On the other hand, many home owners find that either their roof is pointing to the wrong direction or nearby trees shade those areas too much for practical implementation (and the trees are often esthetically pleasing in their own right).

Employers could also see an added value to having these shade-structure charging-stations for their commuting workforce. Recent gasoline price rises have already caused definite modifications to workers commuting habits (shifting noticeably toward greater public transportation use) [26]. However, most workers have simply had to bear the brunt of higher commuting costs. Depending on the accessibility of the workplace to public transportation, it may be a difficulty to attract and retain employees; so an employer might view such a solar collector parking structure as part of a multi-faceted benefits package, like having an on-site daycare or fitness equipment. And, as noted above it is likely that some (or most) of the summertime solar generation capacity will be fed back to the grid or used locally at the workplace anyway, so this immediately offsets some of the installation costs (though with a longer payback period than a stand-alone solar array might have).

The local power utility might also benefit from such an installation strategy. Having greater daytime solar generation may forestall the need for them to add other generating capacity to keep up with growing demand. Also, many regions are developing regulations that *require* greater amounts of renewable generation [27]. Certainly, society benefits by reducing our output of carbon dioxide as the gasoline requirements for commuter traffic would be reduced.

### 4. Conclusions

A coordinated effort to support the development and advancement of electric vehicles for commuter usage is described. Plug-in electric and hybrid vehicles are best suited to daytime charging

with solar collectors that are situated at workplace parking lots. The practical aspects of these systems were described in detail and the overall advantages were outlined. Future widespread electric vehicle use by commuters will depend on having battery pack capacities that are larger than now found in hybrid vehicles. And, workplace solar plug-in parking structures also need to be tested and fielded.

### Acknowledgement

Support from the McLaren Endowment is greatly appreciated.

### References

- [1] "Climate Change 2007", the Fourth Assessment Report, Intergovernmental Panel on Climate Change.
- [2] Lester R. Brown, *Plan B 3.0: Mobilizing to Save Civilization*, W.W. Norton and Co., New York, NY, 2008.
- [3] "High Food Prices—A Harsh New Reality", World Bank report, February 29, 2008, available online from <http://econ.worldbank.org/>.
- [4] Annual Energy Review 2007, Department of Energy, provided online through the Energy Information Administration (EIA): <http://www.eia.doe.gov/>. Transportation overall required 29.10 quadrillion BTUs from overall demand of 106.96, resulting in something over 27% of the overall supply. This is an excellent web resource for many energy data.
- [5] From a Toyota news release on 5/15/2008 <http://www.toyota.co.jp/en/news/08/0515.html>.
- [6] <http://www.calcars.org/priusplus.html>—conversion with lead-acid batteries is quoted as having a 10 mile electric-only range; lithium-ion battery replacement would give a 30 mile range.
- [7] [http://www.plugincenter.com/index.php?page\\_id=7](http://www.plugincenter.com/index.php?page_id=7) – conversion with unknown battery type is quoted as giving a 15–60 mile range.
- [8] <https://www.a123systems.com/hymotion/products/N5.range.extender>—conversion provides 5 kWh charge in Li-ion batteries and is quoted as giving a 30–40 mile range.
- [9] <http://www.solarelectricalvehicles.com/>—this conversion added a 3 kWh supplemental battery pack and is quoted as giving a 20 mile range. They also demonstrated a roof-mounted solar array generating 215 Wp—not really large enough to fully charge the supplemental battery, but interesting nonetheless.
- [10] David Kushner, "The Hack-a-Hybrid Kit", *Business 2.0*, July 2006, vol. 7, issue 6, p. 28.
- [11] Asami Novak, "Hybrids' Next Trick", *Wired*, July 2007, vol. 15, issue 7, p. 76.
- [12] "Electric companies to help develop plug-in hybrid cars", *Design News*, Feb. 2006, p. 36.
- [13] "Plug-in Hybrid Electric Cars: How They'll Solve the Fuel Crunch", *Popular Mechanics*, May 2007.
- [14] <http://www.popsci.com/cars/article/2008-03/how-it-works-tomorrows-hybrid-Volvo-plugin-concept-car-called-the-ReCharge>.
- [15] <http://www.rasertech.com/news/scripts/full-news.php?1216730760>—Raser Technologies is developing F150 fleet plug-in-hybrid light trucks with 100 MPG mileage and 40 mile electric only range.
- [16] W. Kempton, J. Tomic, *J. Power Sources* 144 (2005) 268–279.
- [17] W. Kempton, J. Tomic, *J. Power Sources* 144 (2005) 280–294.
- [18] J. Tomic, W. Kempton, *J. Power Sources* 168 (2007) 459–468.
- [19] C.H. Stephan, J. Sullivan, *Environ. Sci. Technol.* 42 (4) (2008) 1185–1190.
- [20] G. Fontaras, P. Pistikopoulos, Z. Samaras, *Atmosph. Environ.* 42 (2008) 4023–4035.
- [21] [http://rredc.nrel.gov/solar/old\\_data/nsrdb/1991-2005/tmy3/](http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/)—this database for a "Typical Meteorological Year" were recently released in its third version (5/1/2008) and referred to as TMY3.
- [22] Standard measuring conditions for product comparisons are made at 1000 W/m<sup>2</sup> simulated solar illumination brightness. The peak output power is then divided by the illumination brightness times the module's area to arrive at efficiency values. Four manufacturers were compared for similar silicon single or polycrystalline cell modules. No endorsement is implied. Their data sheets can be found here: [http://www.kyocerasolar.com/pdf/specsheets/kd\\_210gx-lp\\_020108\\_web.pdf](http://www.kyocerasolar.com/pdf/specsheets/kd_210gx-lp_020108_web.pdf), [http://www.gepower.com/prod\\_serv/products/solar/en/downloads/gepvp200\\_datasheet.600.pdf](http://www.gepower.com/prod_serv/products/solar/en/downloads/gepvp200_datasheet.600.pdf), [http://www.schottsolar.com/uploads/media/SCHOTT.POLY\\_217-225-232.D.0708.02.pdf](http://www.schottsolar.com/uploads/media/SCHOTT.POLY_217-225-232.D.0708.02.pdf), and [http://solar.sharpusa.com/files/ND-220U2%20spec\\_4-28-08A.pdf](http://solar.sharpusa.com/files/ND-220U2%20spec_4-28-08A.pdf).
- [23] One EV-only button accessory: [http://www.coastaletech.com/electric\\_only\\_mode.htm](http://www.coastaletech.com/electric_only_mode.htm).
- [24] US Department of Transportation, Bureau of Transportation Statistics, *Omnibus Household Survey*, Other related data can be found at their website: [http://www.bts.gov/publications/omnistats/volume\\_03\\_issue\\_04/html/figure\\_02.html](http://www.bts.gov/publications/omnistats/volume_03_issue_04/html/figure_02.html).
- [25] New Jersey's incentive program is described here: <http://www.njcleanenergy.com/>. As of this writing, the NJ incentives (up to 70% rebate for homeowners) have been put on hold because their popularity outran the budget allocation.
- [26] "Gas prices send surge of riders to mass transit", *New York Times*, 5/10/2008.
- [27] New Jersey's version of this regulatory approach is being built into a new "Energy Master Plan" that is nearing completion (<http://www.state.nj.us/emp/>).