VEHICLE INTEGRATED PV: A CLEAN AND SECURE FUEL FOR HYBRID ELECTRIC VEHICLES

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ABSTRACT

Photovoltaic (PV) technology has not been widely utilized as a source of energy for personal transportation. Several experimental projects have evaluated the use of PV integrated into parking structures to charge battery-powered, electric vehicles. Competitions featuring solar-powered vehicles have spawned futuristic looking vehicles propelled solely by electricity produced using vehicle integrated PV. This paper explores the use of vehicle integrated PV (VIPV) for a series hybrid vehicle configuration. Solar would serve as one of several fuel options available to the vehicle owner. This application represents a realistic, near-term possibility for the widespread use of PV as a source of energy for personal transportation.

1. INTRODUCTION

In the United States there is roughly one vehicle for every man, women and child. These vehicles rely almost exclusively on gasoline and diesel fuels derived from petroleum. The combustion of these fuels in vehicle engines produces a variety of pollutants that cause negative human health and ecosystem effects [1]. The U.S. Environmental Protection Agency makes the following statement about mobile (vehicle) sources of pollution:

“Nationwide, mobile sources represent the largest contributor to air toxics. Air toxics are pollutants known or suspected to cause cancer or other serious health or environmental effects.”

Automobiles are responsible for roughly 25% of the nation’s CO$_2$ emissions, a key pollutant linked to global climate change. Furthermore, emissions of NOx and VOCs contribute to ground-level ozone (smog) problems in urban areas [1]. Vehicles account for roughly one-third of all energy consumed in the United States, and over two-thirds of all petroleum [2]. The United States now imports a record 55% of oil from different locations around the globe. Many of the oil rich nations reside in areas with widespread political and social unrest, thus creating the potential for significant price and supply risks.

Much effort has been directed to finding different fuels and technologies for transportation purposes to address the above two issues: environment and supply risks. Different fuels, derived primarily from plant material, have been and continue to be developed to replace gasoline. In addition, much research, and some commercial development, has gone into using an electric motor to provide power to the drivetrain with an on-board battery bank, so called battery-powered electric vehicles (EVs). There has been very little commercial success for EVs. Many analysts view fuel cell technology as the key to creating a new generation of clean vehicles. The President’s recent announcement about increased federal support for fuel cell research is a potentially significant boost to the possible commercialization of fuel cell technology. However,
none of these approaches or technologies are currently widely used for personal transportation.

Hybrid vehicle technology is just emerging as a commercially available option for consumers looking for cleaner, significantly more efficient vehicles. Both Honda (Civic and Insight) and Toyota (Prius) have hybrid models in their showrooms. This paper explores the possibility of integrating solar photovoltaic (PV) cells into the body panels of a series hybrid vehicle, which we call vehicle integrated PV (VIPV). We conclude that VIPV, with series hybrid vehicle technology, represents a near-term opportunity for the widespread use of solar electricity for personal transportation. The relatively modest up-front cost of VIPV and the potential value that a series hybrid might create as a distributed energy resource, may make this an attractive option for potential VIPV series hybrid owners.

2. PV FOR TRANSPORTATION

There have been a number of efforts to utilize PV as an energy source for transportation purposes. In general, PV is used to charge the battery pack in an electric drive vehicle. In several cases, PV was integrated into a parking/shade structure equipped with charging capabilities; the parking spaces underneath the parking structure are then reserved for EVs. For example, the Los Angeles Department of Water and Power (LADWP) built a system that provides 750-kilowatt hours of solar power per day directly into the energy grid [3]. The LADWP carport is also equipped with a rapid, vehicle charging station. Three 2 kW PV systems were installed, for EV charging purposes, at three northern North Carolina schools [4]. One study attempted to assess the performance of a solar electric vehicle charging facility. They found that a 1.87 kW PV array could provide roughly 17,000 miles worth of power for an EV [5].

Alternatively, national and international solar car races have spawned design team competitions to produce PV integrated vehicle prototypes, with no real intention of commercialization. For example, each year the American Solar Challenge invites teams from across the country and globe to compete in a grueling 2,000 mile race using vehicles powered only by energy from the sun [6]. In addition, The World Solar Challenge began in Australia in 1987, where solar powered cars competed in a race across the Australian continent [7]. Teams, many from major universities, have been designing PV integrated vehicles for these types of events for many years. For example, the Massachusetts Institute of Technology’s Solar Electric Vehicle Team, a student organization, designed the Manta GTX shown in Figure 1. This vehicle won first place in the 1995 World Solar Challenge, Sunrayce Class. This vehicle, and others like it, were never intended for commercial applications. In fact, the futuristic look and design of these vehicles would not likely appeal to mass markets.

Fig. 1: The Manta GTX (source: MIT Solar Electric Vehicle Team)

This paper investigates a new application for using PV as a source of power for personal transportation. Specifically, PV cells could be embedded within a vehicle’s body panels that are exposed to sunlight, the hood, roof, and possibly the trunk depending on vehicle design. This would allow a hybrid vehicle to be partially powered using solar. In the next section we explore different hybrid vehicle designs and determine the best system type for this proposed application.

3. HYBRID VEHICLE DESIGN

Hybrid vehicles use both an internal combustion engine and electric motor to power the vehicle. The use of these motors is optimized electronically to deliver the desired performance and achieve superior gas mileage relative to conventional vehicles. In general, hybrid vehicles are categorized as being either a parallel, series, or series/parallel hybrid design. Hybrid vehicles also take advantage of regenerative breaking systems that were developed for battery-powered EVs. These breaking systems allow the vehicle to capture the kinetic energy from breaking and turn it back into electricity, which is then returned to the vehicle’s battery pack.

Parallel electric hybrid designs allow both the internal combustion and electric motors to drive the wheels of the vehicle. The electric hybrids being sold by Honda employ parallel hybrid technology. This vehicle design is more mechanically complicated than the series
hybrids design [8]. In addition, these vehicles require more sophisticated control logic to optimize the performance of the two parallel drive systems.

Another electric hybrid design utilizes a series drivetrain, in which only the electric motor is used to drive the vehicle’s wheels. In this case, the engine is used to drive a generator, which provides power directly to the motor or charges an on-board battery bank. This is considered the simplest electric hybrid design, given that no clutch or complicated multi-speed transmission is required [8].

A third design can be considered a series/parallel mix, in which both the engine and the motor can supply power to the drivetrain. However, this design allows the engine to be effectively disengaged from the transmission. When the engine is disengaged, the vehicle operates similar to a series design. This design capitalizes on the benefits of each design configuration. The Toyota Prius uses the series/parallel electric hybrid design.

An assessment of hybrid technology by the Union of Concerned Scientists categorizes hybrid technology into mild, full, and plug-in hybrids. The plug-in hybrids are characterized as making the greatest strides in providing energy security and improved environmental performance [8]. The full and mild hybrid categories entail less progress in these areas, primarily by differences in hybrid technologies used and how they are deployed. The Toyota Prius receives the full hybrid designation by the UCS because it uses the series/parallel design.

A plug-in hybrid vehicle achieves better environmental performance and greater efficiency gains relative to the full hybrid due to the fact that it allows the batteries to be charged from the electric grid. These vehicles can be thought of as battery powered EVs with a range extender [8]. The engine is used only to turn a generator that provides power to the motor, or charges the battery pack. The electric motor is used to move the wheels, which are equipped with the regenerative breaking described previously.

The series hybrid technology is the appropriate hybrid design that would integrate well with PV electricity. These vehicles could store the power produced from the PV integrated body panels in the battery pack. Series hybrids require a larger battery bank than the parallel hybrid design. Thus, this provides charging opportunities for the VIPV system.

Currently, series hybrids are not commercially available. A prototype, tri-fuel (grid power, gasoline, and natural gas) series hybrid is being built by AC Propulsion, an electric vehicle technology company based in California [9]. Under contract with state and federal agencies, AC Propulsion is converting a VW Jetta to series hybrid technology. The vehicle will be able to charge from the grid, from a gasoline engine, and, while parked, the vehicle could be charged using low-pressure natural gas. This vehicle is also equipped with bi-directional power flow capabilities, so the vehicle could provide power to the grid upon demand. This process of reverse flow of power from electric vehicles to the grid is referred to as vehicle-to-grid (V2G) power.

3.1 Hybrid Vehicles and V2G

The V2G concept suggests that vehicles with electric drive trains could potentially generate revenue for being connected to the grid [10]. Any vehicle with an electric drive train could provide grid-quality power upon demand from a central controller. The California Independent System Operator has demonstrated a radio-controlled system to both charge and draw power from a parked EV [11]. This actually represents a high quality, quick-response power resource, which should be valued at a premium in power markets. Furthermore, one study suggests that owners could generate a positive cash flow for allowing their vehicle to serve different power markets [12]. Another study evaluated the possibility of using the electric vehicle’s battery bank as buffer storage to enhance the capacity value of photovoltaic (PV) installations [13].

Plug-in hybrid electric vehicles are particularly well suited for V2G power. These vehicles have larger battery packs than other hybrid designs and, if the stored energy is accessed for V2G, there is no impact on the vehicle owner’s mobility. Currently, the Electric Power Research Institute (EPRI) is investigating the potential of plug-in hybrid technologies [14]. In the next section we discuss another potential value added to electric series hybrid vehicles, PV integrated body panels.

4. VIPV SERIES HYBRID CARS

There are many different types of PV technology commercially available. In recent years, many projects have highlighted the use of building-integrated PV (BIPV) [15]. PV is now being integrated into different building products to serve BIPV applications. For example Uni-Solar offers SmartRoofSM shingles and
laminates, a residential PV roofing product [16]. In addition, others companies have designed commercial and industrial roofing systems integrated with PV, and semi-transparent building facade materials integrated with PV [14].

Similar to BIPV, PV technology could be integrated in the body panels of a vehicle. As discussed above, a series electric hybrid would be a good technological match with vehicle integrated PV (VIPV). Given that series hybrid technology could be deployed with a variety of vehicle body types, we assess the potential PV array size likely to fit on different vehicle types. Table 1 lists several current vehicles with the dimensions of the vehicle’s body panels that could capture solar energy, and an estimate of the PV capacity. The amount of available PV power is based on the surface area of the vehicles’ roof, hood, and trunk panels. It is assumed that single crystal photovoltaic technology would be integrated into the vehicle’s body panels. This technology has the highest conversion efficiency and thus the greatest energy output. However, more technical analyses would be needed to determine the appropriate PV technology to deploy in VIPV applications.

**TABLE 1: VIPV POTENTIAL FOR SELECT VEHICLE BODY TYPES**

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Body Panels’ Area</th>
<th>PV Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jeep Grand Cherokee</td>
<td>3.93 m²</td>
<td>497 watts</td>
</tr>
<tr>
<td>Honda Accord</td>
<td>3.46 m²</td>
<td>438 watts</td>
</tr>
<tr>
<td>Suburu Forester</td>
<td>3.68 m²</td>
<td>465 watts</td>
</tr>
<tr>
<td>Buick LeSabre</td>
<td>5.31 m²</td>
<td>671 watts</td>
</tr>
<tr>
<td>Chevrolet Cavalier</td>
<td>3.22 m²</td>
<td>407 watts</td>
</tr>
</tbody>
</table>

4.1. **VIPV Fuel Contribution**

The technical specifications for the prototype, tri-fuel, series, hybrid being produced by AC Propulsion Inc., are used to estimate what percentage of transportation fuel could be expected from a VIPV system. This vehicle is being built with a 9 kWh lead-acid battery pack [9]. This would provide between 30 to 40 miles range when operating in battery-only mode. This translate into roughly .206 kWh / mile, assuming an 80% depth of discharge and 35 mile range.

The output of the VIPV system will depend on many factors, from region of the country to personal parking habits. Ideally, a VIPV hybrid car should be parked with good southern exposure, like on the top-level of a parking garage. Table 2 indicates the potential energy production from a VIPV hybrid with 500 watts of PV embedded in the body panels, given different capacity factors. In addition, table 2 lists the total miles traveled on the PV power assuming an efficiency of 0.206 kWh / mile.

**TABLE 2: VIPV ENERGY AND PV MILES**

<table>
<thead>
<tr>
<th>PV Capacity Factor</th>
<th>Annual kWh Production</th>
<th>PV Miles</th>
</tr>
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<tbody>
<tr>
<td>30%</td>
<td>1,051</td>
<td>5,103</td>
</tr>
<tr>
<td>25%</td>
<td>876</td>
<td>4,252</td>
</tr>
<tr>
<td>20%</td>
<td>701</td>
<td>3,402</td>
</tr>
<tr>
<td>15%</td>
<td>526</td>
<td>2,551</td>
</tr>
<tr>
<td>10%</td>
<td>350</td>
<td>1,701</td>
</tr>
<tr>
<td>5%</td>
<td>175</td>
<td>850</td>
</tr>
</tbody>
</table>

(Note: Assumes 500 watt PV system and 80% system efficiency.)

Table 2 suggests that the PV would provide enough power for only a part of the total annual miles traveled in a vehicle. For example, assuming a 20% PV capacity factor a VIPV hybrid could travel almost 3,500 miles on the PV power alone, roughly 25% of 15,000 miles traveled annually. Alternatively, a “fold-out” system could be designed with lightweight PV materials that stores in the trunk or interior of the vehicle. The system would be attached to a mechanical mechanism that could easily be folded out and positioned towards the sun when the vehicle is parked. This would provide additional charging for the vehicle, augmenting the power production from the PV integrated in the car’s body panels. As such, another 500 watt, auxiliary PV system could allow a VIPV car owner to meet 50% of their energy requirements for personal transportation from solar energy.

The widespread application of VIPV could represent a significant power resource for the nation. If the 200 million cars in the United States had 500 watts of PV integrated into their body panels, this would represent a 100 GW grid-connected resource. This is roughly one seventh of the total installed generating capacity in the United States.

4.2. **VIPV Costs and Benefits**

The incremental cost of integrating PV into a vehicle’s body panels is relatively modest when compared to the
cost of a new car. At $3 dollars per watt, a 500 watt VIPV system would add $1,500 dollars to the price of a new car. The incremental costs for power electronics should be rather limited, given that the series hybrid would have an inverter and other necessary power logic to control the electric motor and drivetrain. However, the annual fuel cost savings from the VIPV system would be rather marginal. Assuming $1.50 for a gallon of gasoline and fuel economy of 27 miles-per-gallon, the VIPV would save under $200 each year in avoided fuel costs. Thus, it would take over 7 years for the incremental PV costs to payback from avoided fuel costs.

Another way to look at the costs and benefits is to estimate costs per mile. Again, assuming 27 miles-per-gallon and gasoline prices at $1.50 per gallon, this translate into almost 6¢/mile. Whereas, over the ten year life of a VIPV vehicle, the solar could provide roughly 35,000 miles at a cost of $1,500, which translates into roughly 4¢/mile. There are other more generic benefits of owning a series hybrid in the form of reduced maintenance costs etc. An analysis of these benefits is beyond the scope of this paper.

As mentioned before, a grid-connected series hybrid could serve V2G markets if they emerge. As the studies mentioned earlier suggest, V2G power could potentially serve to generate a cash flow for an electric vehicle owner, helping to offset the higher initial capital cost [10]. Thus, V2G offers another potential value proposition for owners of a VIPV hybrid electric car.

Another potential benefit to the owner of a VIPV car is the fact that having a solar fuel option reduces the risks associated with possible fuel shortages and price spikes. Even if gasoline supplies were eliminated, a VIPV car owner could still maintain some degree of mobility. This concept may also have an appeal in other applications aside from personal transportation. The military may have an interest in an advance vehicle that relies only on solar for energy.

5. CONCLUSIONS

Personal transportation imposes significant environmental and security risks on our society. The combustion of gasoline in internal combustion engines releases a variety of pollutants that result in negative human and ecosystem health impacts. Furthermore, the exclusive reliance on petroleum for fuel creates the potential for significant supply shortages and price risks. Consumers have few choices when it comes to environmentally friendly personal transportation options. The emergence of hybrid vehicles represents an exciting option for consumers looking for clean, fuel efficient vehicles. This paper suggests that these vehicles could become even more environmentally sound by integrating solar cells into the vehicles’ body panels.

A variety of different efforts have been undertaken to utilize PV power for personal transportation purposes. PV integrated into parking structures for electric vehicle charging has been demonstrated in different parts of the country. Alternatively, university design teams have created solar-only power vehicles for national and international solar race competitions. Both of these attempts to use PV for personal transportation don’t offer the promise for widespread use of PV power for transportation. Battery powered electric vehicles have not enjoyed widespread commercial acceptance. In addition, the futuristic and impractical designs of solar competition cars make them unlikely candidates for commercial success.

Hybrid electric technology is now commercially available to consumers. Honda and Toyota now offer off-the-lot hybrid electric vehicles. VIPV with hybrid electric vehicles could offer a near-term opportunity for PV to satisfy a significant portion of a vehicle owner’s energy needs. In particular, series hybrid technology with PV integrated within the car’s body panels, could potentially provide 25% of the energy requirements for personal transportation. While both the costs and benefits of VIPV are relatively modest, the “solar” car sales proposition could appeal to many potential consumers. Furthermore, the potential for series electric hybrid to provide V2G power further enhances a VIPV car’s value to consumers.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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