Title

Role of PV generated DC power in transport sector: Case study of plug-in EV

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Role of PV Generated DC Power in Transport Sector: Case Study of Plug-in EV

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***Abstract*—The challenge of meeting the corporate average fuel economy (CAFE) standards of 2025 is leading to major developments in the transportation sector, not the least of which is the utilization of clean energy sources. Solar energy as a main source of on-board fuel has not been extensively investigated. This paper reports on the usage of solar energy for transportation and investigates the extended driving range, the economic value, and the energy return of investment (EROI) of adding on-board photovoltaic (PV) technologies to plug-in electric vehicles (EV). The study develops a comprehensive PV system model and optimizes the solar energy to DC electrical power output ratio for on-driving mode. In times of no-use, the proposed system transforms into a flexible energy generation system that can be fed into the grid and used to power DC electrical devices in homes and offices. The results show that by adding on-board PVs to cover less than 50% of the projected horizontal surface area of a typical passenger EV, up to 50% of the total daily miles traveled by a person in the U.S. could be driven by solar energy. For the lifetime driving cost, even with low electricity price (0.13 $/kWh), adding on-board PV shows a positive impact if the system is operating in high solar energy environment (e.g. Arizona). If the electricity price is high ((0.35 $/kWh), there is positive economic impact even in low solar energy environments (e.g. Massachusetts). The energy payback time (EPBT) is found in a range 3.5-4.8 years, depending on where the system operates and energy return of investment (EROI) is between 6.2 to 8.6 times.**

Keywords*— *DC electricity; Grid; Photovoltaic; Plug-in Electric Vehicle; Solar Energy; Sustainable Transportation

I. INTRODUCTION

Developing sustainable transportation technologies are the current need to reduce environmental concerns along with high-energy demand in the conventional transportation sector. In this work, the use of solar energy by means of on-board photovoltaic (PV) modules in surface of transportation is investigated, particularly for a plug-in electric vehicle (EV) case study. Solar energy is a free, sustainable, and clean source and most vehicles are rarely driven for long distances in the US, with the average vehicle trip approximately 36 miles and the average driving duration of less than an hour [1]. On-board PVs for vehicle configurations are discussed in [2]-[5]. However, there is incomplete understanding about the actual contribution in reducing energy consumption as well as the economic value of adding on-board PVs to plug-in EV.

This study focuses on developing a comprehensive photovoltaic (PV) system model for the vehicle application. It optimizes the solar energy to the DC electrical power output ratio to provide DC power for vehicle propulsion in the driving mode. In times of no-use, the proposed system transforms into a flexible energy generation system that can be fed into the grid and used to power electrical devices in homes and offices. The study estimates the economic value, the energy payback time (EPBT), and energy return of investment (EROI) for the proposed application.

II. ON-BOARD PV SYSTEM MODEL FOR TRANSPORTATION

Fig. 1 shows the proposed model. The PV system provides DC power on-board to run the propulsion system of plug-in electric vehicle (EV). In times of no-use, the proposed system output can fed to the grid or use to operate local DC electrical devices in homes or offices.

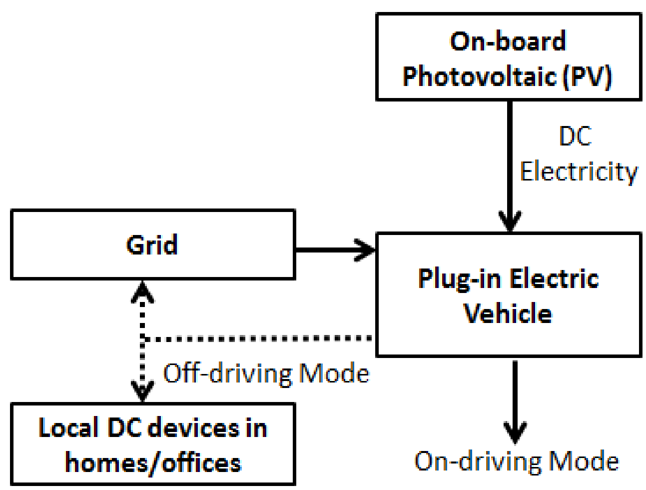

Fig. 1. Proposed on-board PV application for transportation

A. Photovoltaic (PV) Device

A solar PV cell is an electronic device (pn-junction) that converts electromagnetic radiation near the visible range into direct current (DC). The PV module is a packaged assembly of individual PV cells. In previous work, we developed two novel knowledge-based systems for selecting the optimum PV module type option for vehicle application [6], [7]. The mono-Si PV type was selected as the best current commercial option.

The equivalent PV cell (module) circuit is modelled as shown in Fig. 2. It consists of current source, parallel diode, series resistance (R_s), and shunt or parallel resistance (R_{SH}). The current (I) and the voltage (V) are calculated using (1)-(4) [8], [9]. The current generated by the incident light (I_{pv}) depends on sun irradiation. The diode current (I_d) is based on the Shockley diode equation.

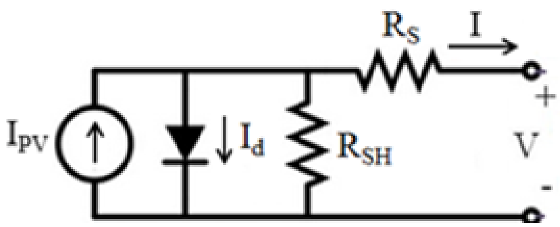

Fig. 2. Ideal and practical PV equivalent circuit

The R_s reflects the internal resistances in the gridlines, busbar, and the interference between silicon and the contacts. The R_{SH} is typically due to the manufacturing defects. In previous work, we reviewed the main defects and shunts [10], [11].

$$I = I_{PV} - I_d - \frac{V + R_S.I}{R_p} \quad (1)$$

$$I_{PV}(T) = \frac{G}{G(nom)}\left[I_{SC}(T_{1,nom}) + \left(\frac{I_{SC}(T_2) - I_{SC}(T_1)}{(T_2 - T_1)}\right).(T - T_1) \right] \quad (2)$$

$$I_d = I_0\left(e^{\frac{q(V + I.R_S)}{nkT}} - 1 \right) \quad (3)$$

$$I_0 = \frac{I_{SC}(T_1)}{\left(e^{\frac{q.V_{OC}(T_1)}{nkT_1}} - 1 \right)} \times \left(\frac{T}{T_1}\right)^{\frac{3}{n}} \times e^{\frac{q.V_q(T_1)}{nk\left(\frac{1}{T} - \frac{1}{T_1}\right)}} \quad (4)$$

Where: I_{sc} is the short circuit current, V_{oc} is the open circuit voltage, I_0 is the reverse saturation current, n is the diode ideally factor, q *is* the electron charge, K is the Boltzmann constant, *G(nom)* is the nominal irradiation which equal 1000 W/m^2, T_1 is the reference temperature (25° C). G is the global solar irradiation and T is the cell temperature.

A Transcendental Equation (5) is generated by substituting (2)-(4) in (1) and it does not have a direct solution.

$$I - f(G, T, V_g, n, R_s, R_{Sh}, I, V) = 0 \quad (5)$$

A numerical solution is found by minimizing the error $I - f(I, V) = 0$ for a set of V values to find the corresponding I values. The four-parameter approach is used for modelling, which means that R_p is assumed infinite and ignored. The other unknown parameters (I_L and I_o) are calculated. The V_g is set to 1.12, which is a typical value for crystalline silicon PV module. The other parameters (n and R_s) are estimated using curve-fitting approach where these parameters' values are tuned with the objective function is to minimize the maximum PV module power to be within the accuracy range of the reported peak power of the PV module manufacturer data. The modelling for parameters G and T are discussed in the next sub-sections. The mono-Si PV module from Sunpower Company [12] is used to validate the results of the proposed model by comparing the actual manufacturer' datasheet data and the predicted model results as shown in Fig. 3. The solid lines represent the actual *I-V* curves reported by manufacturers and the "triangle and circle" are the proposed model results.

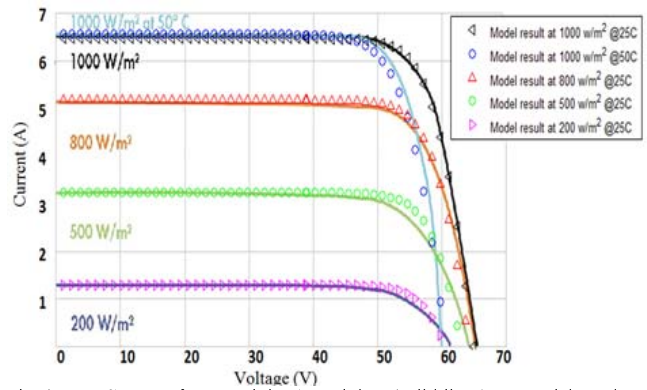

Fig. 3. I-V Curves of PV module: Actual data (solid lines) vs. model results (circles/triangles)

B. Modeling Solar data (G) and Solar Cell Temperature (T)

Fig. 4 shows the solar map in terms of annual (G) [13]. Here, two cities were selected, which represent the extremities, in terms of available solar energy; (i) Phoenix in Arizona and (ii) Boston in Massachusetts.

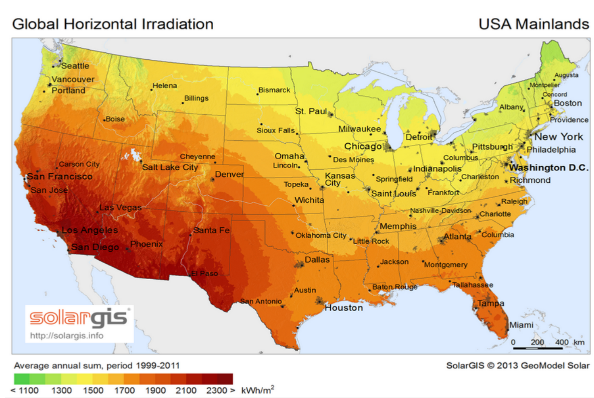

Fig. 4. Annually global horizontal irradiation (G) in US states [13]

The mounting structure option of a PV solar module on vehicle surface affects (T) and the PV performance. An empirically based thermal model [14] is used in this work to estimate the thermal performance of PV. The optimum configuration is found to be the open rack: glass/cell/glass configuration.

C. *Maximum power point (MPP) tracking algorithm and energy Storage*

The MPP implies the optimum voltage and optimum current that the PV system needs to work. In this work, the incremental conductance (IncCond) algorithm [15] is implemented to track the MPP points. The Li-ion polymer battery is modeled, since this new class of batteries that exhibited promising efficiencies for future EV market, the full specification and analysis are found in previous work [16]-[18].

D. *Modeling Vehicle Energy at Wheels*

The energy demand (E_W) at the wheels for a given driving cycle and given vehicle, assuming a road grade is zero, is calculated using (6) [19].

$$E_W = \frac{1}{2}.\rho_a.C_d.A_f.\int_{Cycle} v^3 dt + M_v.g.C_r.\int_{Cycle} v\ dt + 1.1.M_v.\int_{Cycle} V\frac{dV}{dt} \quad (6)$$

Where, M_v is the vehicle mass in (kg), C_d is the dimensionless aerodynamic drag coefficient, ρ_a is the density of the ambient air, A_f is the frontal projected area, C_r is the rolling resistance coefficient, and v is the vehicle velocity.

E. *Shadow and Sky Clearness and Tilting*

The GHI consists of direct (DNI) and diffused horizontal irradiances (DHI). DNI that reaches the PV module is affected by shadows. The DHI component is affected and minimized based on the clearness of the sky. Equations (7) and (8) are proposed to calculate GHI in both parking and driving modes.

$$\mathrm{GHI}_{\text{Parking Mode}} = \alpha_P \times \mathrm{DNI} \times \cos(\theta) + \Psi_p \times \mathrm{DHI} \quad (7)$$

$$\mathrm{GHI}_{\text{Driving Mode}} = \alpha_d \times \mathrm{DNI} \times \cos(\theta) + \Psi_d \times \mathrm{DHI} \quad (8)$$

Where, α , is the shadow factor varying between $0 \le \alpha \le 1$ and Ψ ,is the sky clearness factor varying between $0 \le \Psi \le 1$. If α =1, there is no shadow while if α =0, means there is complete shadow. If Ψ =1, then the sky is clear, while Ψ =0, means the sky is blocked. Generally, α & Ψ factors change with time and depend on many factors as weather, surroundings, locations, etc. In addition, α & Ψ could affect the PV module partially and not the entire module and could have different values in different sections of the module.

In the case of tilting, the results show that for on-board vehicle application, if the PV module is fixed, the optimum tilt angle is horizontal. This also eliminates any problems that may arise due to aerodynamics.

III. Results and Discussion

The area of the PV base module [12] is 1.63 m^2 (1.559 m X 1.046 m). Typically, the vehicle surface can be fitted with this PV module width. The assumed installed PV area is 3.26 m^2 with the assumption that the width is constant and the length is variable with series connection to obtain the required PV area (constrained by a constant PV efficiency). Two scenarios are assumed, the worst scenario is referred to the vehicle is driven in December in Boston, MA and the best scenario is referred to June in Phoenix, AZ. This makes the results reflect mostly all U.S states at any time. The vehicle combined driving range is assumed 77 miles, this is close to Ford Focus EV 2014 range and the vehicle lifetime is assumed 160,000 miles, which is similar to GREET assumption.

A. *Pure PV Solar Daily Driving Ranges (PV Range Extender)*

The daily pure PV solar range extender is estimated by adding the proposed PV modules to the assumed vehicles (see Fig. 5). Here, all the vehicles are electric and the vehicle efficiency (Wh per mile) is located in the y-axis. The weight is only increased by the PV module and the mounting weight, which is discussed in [6].

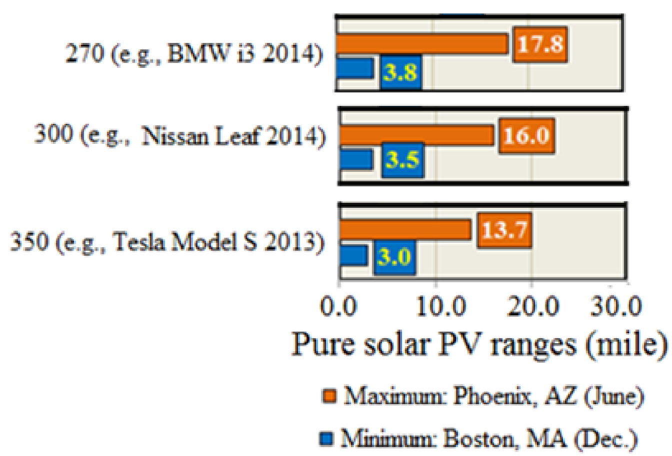

Fig. 5. Pure solar PV driving range (range extender)

B. *Cost Analysis of Pure Plug-in EV vs. Plug-in EV with On-board PV*

The life cycle cost of the powertrain and the fuel price for each driven mile are estimated. The cost of the battery and motor are calculated using (9) and (10) [20].

$$\text{Motor and controller} = \$21.7/\text{kW} + \$425 \quad (9)$$

$$\text{Battery} = \$22/\text{kW} + \$500/\text{kWh} + \$680 \quad (10)$$

The cost of the battery was around 1000 $/kWh in 2008, while it has dropped to 325 $/kWh in 2014 and it is expected that the price will further be dropped to 125 $/kWh by 2022 with 100,000 annual production [21]. The vehicle lifetime is considered 160,000 miles as the GREET assumption; however, the life span of the PV module is around 30 years. The assumption here is that since the calculation is just based on vehicle lifetime, the PV module could be transferred to another application after the vehicle is recycled. The assumed vehicle is a conventional mid-size plug-in EV with motor size 92 kW and 25 kWh battery size. The electricity price is different from location to location, hence two electricity prices are assumed with a low price of 13 ¢/kWh (Average U.S 2014) and a high price of 35 ¢/kWh (Germany). We assumed scenario 1 is based on current market price of the battery, PV, and motor. Scenario 2 is based on future projected prices. For each scenario the assumption is that the vehicle will be driven in two cities, the first being a low solar energy area (e.g., Boston, MA) and the second an area with high solar energy (e.g., Phoenix, AZ). The detailed calculations and assumptions can be found in Table I.

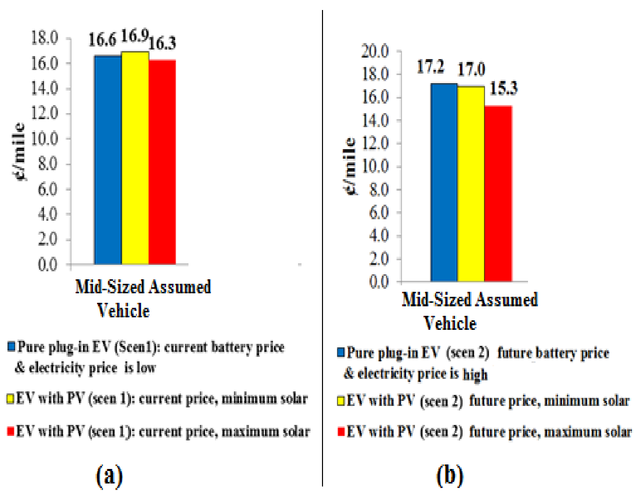

Fig. 6. Lifetime driving cost of adding PV for plug-in EV

As shown, even with low electricity price, adding PV showed a positive impact on the lifetime cost if the system is operating in a high solar energy environment. For the high electricity price case, the results also showed a positive impact on cost in both low and high solar energy regions.

C. *Energy payback time (EPBT) and Energy return of investment (EROI)*

The EPBT is defined, as the period required of a PV system to generate the same amount of energy used to produce the system itself. The life span of PV modules is 30 years and the module efficiency is degraded linearly by 0.7% per year. The lifetime energy generated by the proposed system for PV lifetime is calculated as 34 MWh in Phoenix, AZ and 24.5 MWh, in Boston, MA, respectively. The average annual electricity consumption for a U.S. household is 10,837 kWh [23]. This means that the lifetime-generated energy by the proposed PV module in Phoenix, AZ is the equivalent of what an American household residential utility customer consumed in more than 3 years.

The total energy needs to produce the PV module from the life cycle point of view is called embodied energy and reported for mono-Si PV as 3513 MJ/m^2 [24] and 5253 MJ/m^2 [25]. The total embodied energy for the proposed system is 14,288 MJ (3.97 MWh), which is an average value for the reported embodied energy multiplied by the PV area. The estimated EPBT is in a range from 3.5 to 4.8 years, depending on where the system is operating in the U.S. The EROI of this proposed system is between 6.2 to 8.6 times.

Table I. Economic analysis of adding a PV on-board for plug-in EV

Row #	Component	Quantity	Current Price ($)	Future Price ($)
1	PV Module ($/W) [22]	1 W	0.88	0.51
2	PV Module ($) after 7% tax	654 W	616	357
3	Mounting	1	100	50
4	Electric Motor Price ($)	92 kW	2,421	
5	Battery Price ($)	25 kWh	14,446	4,821
6	Electricity pure plug-in: Low Price (13¢/kWh)		6,240	
7	Electricity pure plug-in EV- High price (35 ¢/kWh)		16,800	
8	On-board Charger		500	
9	Maintenance		3,000	
10	Minimum solar: electricity low		5,956	
11	Maximum solar: electricity low		4,943	
12	Minimum solar: electricity high		16,036	
13	Maximum solar: electricity high		13,309	
Scenario 1	Lifetime cost pure plug-in EV($): Scenario 1	For 160,000 miles	26,607	Current price and low electricity : Sum rows 4,5,6,8,9
Scenario 1	Scenario 1: Lifetime cost PV & plug-in EV($): minimum solar (Boston, MA)	For 160,000 miles	27,039	Current price and low electricity : Sum rows 2,3,4,5,8,9, 10
Scenario 1	Scenario 1: Lifetime cost PV & plug-in EV($): maximum solar (Phoenix, AZ)	For 160,000 miles	26,026	Current price and low electricity : rows 2,3,4,5,8,9, 11
Scenario 2	Scenario 2: Lifetime cost pure plug-in EV($):	For 160,000 miles	27,542	Future Price and high electricity: Rows 4,5,7,8,9
Scenario 2	Scenario 2: Lifetime cost PV & plug-in EV($): minimum solar (Boston, MA)	For 160,000 miles	27,185	Future Price and high electricity: Rows 2,3,4,5,8,9, 12
Scenario 2	Scenario 2: Lifetime cost PV & plug-in EV($):maximum solar (Phoenix, AZ)	For 160,000 miles	24,457	Future Price and high electricity: Rows 2,3,4,5,8,9, 13

D. DC Electronic Devices

The proposed system, in times of no-use, transforms into a flexible energy generation system that can be fed into the grid and used to power electrical devices in homes and offices. The annual energy generated by the proposed system is enough to operate the combination of all the devices shown in Table II [26].

Table II. Electronic equipment and the average energy used in each mode and per year [26]

Product	Average Annual Energy Use (kWh)
LCD TV (<40")	77
DVD	13
Desktop Computer	255
Laptop Computer	83
LCD Monitor	70
Computer Speakers	20
Modem	50
Wireless Router	48
USB Hub	18
Printer	15
Hand-Held Vacuum	29
Cordless Phone	26
Electric Toothbrush	14
Shaver	11
MP3 Player	6
Cell Phone	3

IV. Advantages of Using PVs On-board vs. off-board in Transportion

While the PV could provide the energy for transportation off-board (stationary), there are advantages and disadvantages for using PVs on-board versus off-board as summarized in Table III. The main advantages of using PVs on-board are no extra infrastructure or energy storage is needed. Besides, it provides the ability to cut idling, if use with heavy vehicle application. The challenge is design complexity.

Table III. Using PVs On-board vs. Off-board for Transportation

	Proposed application (On-board)	Stationary (Off-board)
Design Complexity	More	Less
Weight Constraint	Yes	No
Extra-Energy Storage	No (if use for plug-in EV)	Always Yes
Application	Propulsion, Cut idling (if use with large and heavy vehicle)	Propulsion
Infrastructure	No	Yes
Charging	While parking/driving	Parking
Utilize Solar energy	Any place	Limited at particular stationary place

V. Conclusion

A comprehensive on-board PV system model is developed for plug-in EV applications. The proposed model is optimized for the optimum solar energy-to-direct current (DC) electrical power ratio. This modeling entails analyzing the geographical solar location, thermal performance, MPPT algorithm, energy storage, tilt option, shadow and sky clearness, and mounting configuration, and tracking options.

The proposed work covers mostly all U.S states with different cost analysis scenarios for current and future prices. Estimates of the pure PV solar range (PV range extender) for 3 vehicles are presented, The results showed that the daily driving range could be extended from 3.0 miles to 18 miles based on vehicle specifications, locations, and time. A comparison of the lifetime driving cost ($ per mile) of a pure plug-in EV versus a plug-in EV with PV showed, even with low electricity price ($0.13/kWh), adding PV showed a positive impact on the lifetime cost if the system is operating in a high solar energy environment. In the high electricity price case ($0.35/kWh), the results also showed a positive impact on cost in both low and high solar energy regions. The PV modules did, however outlive their vehicle hosts, having nearly 16 years of operation left for use in different applications. Although this indicates the addition of the PV to the vehicle is a value added alternative, it was not considered in this study.

The fact that the output of this system is direct current (DC) electricity rather than alternative current (AC) electricity, this reduces the wasted energy cost in the generation, transmission, and conversion losses between AC-DC electricity to reach the grid. Thus, this system can potentially reduce the dependency on the grid in third world countries where the energy consumption per home is limited and the grid is unstable or unreliable, or even unavailable.

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