

Impacts of Adding Photovoltaic Solar System On-Board to Internal Combustion Engine Vehicles Towards Meeting 2025 Fuel Economy CAFE Standards

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ABSTRACT

The challenge of meeting the Corporate Average Fuel Economy (CAFE) standards of 2025 has led to major developments in the transportation sector, among which is the attempt to utilize clean energy sources. To date, use of solar energy as an auxiliary source of on-board fuel has not been extensively investigated. This paper is the first study at undertaking a comprehensive analysis of using solar energy on-board by means of photovoltaic (PV) technologies to enhance automotive fuel economies, extend driving ranges, reduce greenhouse gas (GHG) emissions, and ensure better economic value of internal combustion engine (ICE) -based vehicles to meet CAFE standards through 2025. This paper details and compares various aspects of hybrid solar electric vehicles with conventional ICE vehicles. Different driving locations, vehicle sizes, various driving patterns and different cost scenarios are used in order to enhance the current understanding of the applicability and effectiveness of using on-board PV modules in individual automobiles and ensure an accurate representation of driving conditions in all U.S. states at any time. These times and location-dependent results obtained over a year show an increase in the combined mile per gallon (MPG) at noon in the range of 2.9-9.5% for a vehicle similar to a Tesla S, and a significant increase in the range of 10.7-42.2% for lightweight and aerodynamic efficient vehicles. In addition, by adding on-board PVs to cover less than 50% of the projected horizontal surface area of a typical mid-size vehicle (e.g., Toyota Camry or Nissan Leaf), up to 50% of total daily miles traveled by an average U.S. person could be driven by solar energy. Also, the return on investment (ROI) of adding PVs on-board with ICE vehicle over its lifetime shows only negative values when the price of gasoline remains below \$4.0 per gallon and the vehicle is driven in low-solar energy area (e.g., Boston, MA). The same ROI is more than 250% if the vehicle is driven in high-solar energy area (e.g., Arizona), even if the gasoline price remains low. For future price scenarios, this ROI is much higher - nearly 10 times the investment cost under some scenarios, with the assumption of an eventual decline in battery costs. With regard to environmental impacts, significant gasoline gallons savings (~500-3400) and CO₂ emission reduction (~5.0 to 34.0 short tons) are achieved.

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INTRODUCTION

Environmental concerns, high energy demand in the transport sector, and strong government regulations for 2017-2025 passenger cars and light trucks to reduce greenhouse gas (GHG) emissions and improve Corporate Average Fuel Economy (CAFE) standards [1] have led to increased focus on creating sustainable transportation technologies, not the least of which is the utilization of clean energy sources. U.S. Department of Energy, national labs, automotive OEMs, and academic researchers have been engaged in developing many solutions and models (e.g., ADVISOR model, PSAT, FASTSim, VISION, and GREET Model) to predict vehicle performance, emissions, and cost of alternative Powertrain technologies with different energy paths.

All above-mentioned efforts have overlooked the investigation of solar energy as an auxiliary on-board fuel. Widespread use of solar energy - a free, sustainable, renewable, and clean energy source - in fuel-efficient

automobiles can ensure energy independence for U.S. while minimizing environmental impacts. Solar PV remains a promising technology for managing the on-board power systems of hybrid electric vehicles (HEVs). Technological advances in solar PVs have brought about efficiency improvements and cost reduction, and are expected to accelerate their inclusion in the automotive design process [2]-[4].

Although configurations exist for including on-board PVs in vehicles [5]-[9], current understanding on the efficacy of adding on-board PV technologies to internal combustion engines (ICE) for different vehicle sizes in different U.S. locations under various driving scenarios remains incomplete. This paper is the first attempt at undertaking a comprehensive analysis of using solar energy on-board by means of PV technologies to enhance automotive fuel economies to meet CAFE standards through 2025 and extending driving ranges for ICE vehicles. In addition, in this paper, we also estimate the economic

return on investment (ROI) and environmental impacts of adding on-board PVs to ICE vehicles under different scenarios. The proposed assessment methodology includes three different travel patterns in different U.S. states, covering different cost analysis scenarios for current and future prices.

MODELING ON-BOARD PV SYSTEM FOR ICE VEHICLES

Geographical Location

Total incident solar radiation (in kWh/m²) for a specific period is known as global horizontal solar irradiation (G or GHI). GHI has two components: DNI and DHI. DNI, or direct normal irradiance, represents the solar energy that reaches the ground directly (in a straight line) from the sun, while DHI, or diffused horizontal irradiance, is derived from either scattering or diffusion of molecules and particles in the atmosphere. As the annual GHI in U.S. varies from state to state (see Figure 1 [10]), two cities which represent the extremities in terms of available solar energy were selected; (i) Phoenix, AZ and (ii) Boston, MA.

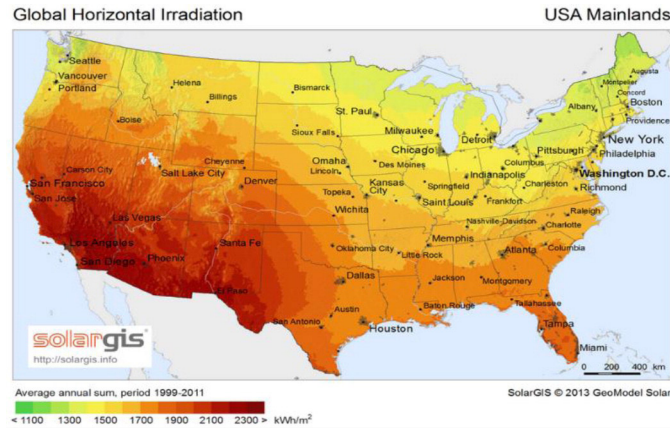


Figure 1. Annually global horizontal irradiation (G) in U.S. states [10]

PV Device

PV module is a packaged assembly of individual PV cells. A solar PV cell is an electronic device (p-n junction) that converts electromagnetic radiation near the visible range into direct electric current (DC). Previously, we developed two novel knowledge-based systems to evaluate and select the optimum solar PV module type for on-board vehicle applications [7], [8]. Mono-crystalline silicon (mono-Si) PV type was selected as the current best commercial option. The equivalent PV cell (module) circuit is modeled as shown in Figure 2 - consisting of a current source, a parallel diode, a series resistance (R_s), and a parallel (shunt) resistance (R_p). Four-parameter approach is used for modeling, which means that R_p is assumed to be infinite and is hence ignored. Current (I) and voltage (V) are calculated using Equations (1), (2), (3), (4) [11], [12]. The current generated by incident light (I_{pv}) depends on sun irradiation. R_s reflects the internal resistance, while R_p is typically due to manufacturing defects [13], [14].

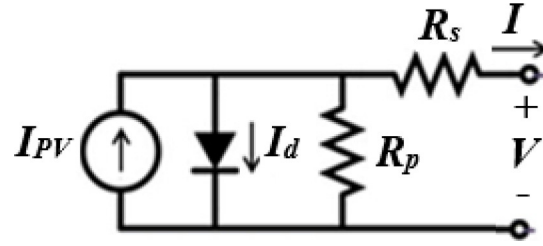


Figure 2. PV device equivalent circuit

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

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

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

$$I_0 = \frac{I_{SC}(T_1)}{\left(e^{\frac{q \cdot V_{oc}(T_1)}{nkT_1}} - 1 \right)} \times \left(\frac{T}{T_1} \right)^3 \times e^{\frac{q \cdot V_g(T_1)}{nk \left(\frac{1}{T} - \frac{1}{T_1} \right)}} \quad (4)$$

A transcendental Equation (5), which does not have a direct solution, is generated by substituting Equations (2), (3), (4) in Equation (1).

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

Parameters I_L and I_o are calculated. V_g is set to 1.12, a typical value for crystalline silicon PV module. Other parameters (n and R_s) are estimated using curve-fitting approach, where the values of these parameters are tuned, with the objective function being to minimize the maximum PV module power to be within the accuracy range of the reported peak power of the PV module manufacturer data. Highly efficient mono-Si PV module, developed by the Sunpower Company [15], is used to validate the results of the proposed model by comparing the actual manufacturers' data and the predicted model results, as shown in Figure 3. Solid lines represent the actual I - V curves reported by manufacturers, while the "triangle and circle" are the results of this proposed model. All the curves at 25°C unless otherwise is indicated.

In this work, an incremental conductance algorithm [16] is implemented in order to track the maximum power points, implying the optimal voltage and current that the PV system needs to work. Opting for a mounted structure of PV solar module on the vehicle surface affects both temperature (T) and the PV module performance. An empirically based thermal model [17] is used to estimate the thermal performance of PV. The optimum configuration of the PV module is observed to be the open rack/glass/cell/glass configuration.

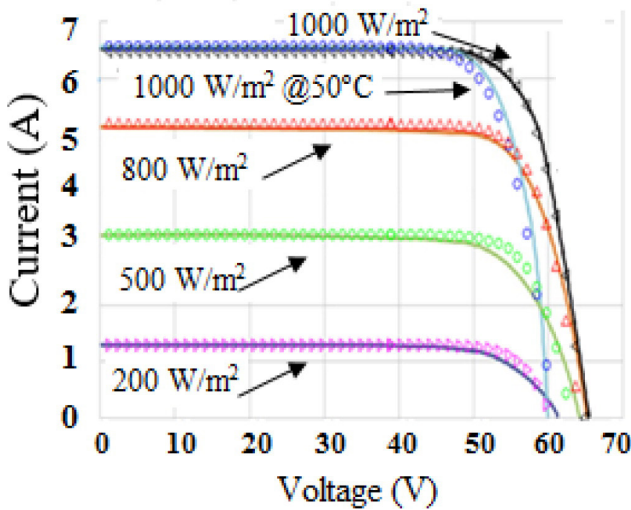


Figure 3. I-V Curves of PV module: Actual data (solid lines) vs. model results (circles/triangles)

Shadow and Sky Clearness

DNI that reaches the PV module is affected by shadows, while, DHI component is affected by the clearness of the sky. The solar data used here is the typical daily solar irradiance data that's collected by the National Renewable Energy Laboratory (NREL) / National Solar Radiation Data Base (NSRDB). It is called Typical Meteorological Year 3 and measured on an hourly base over 30 years based on empirical radiation data collected by meteorological station and include local weather variation which can dramatically change the radiation intensity [18].

Equations (6) and (7) are used to calculate GHI in both parking (p) and driving (d) modes.

$$GHI_{\text{Parking Mode}} = \alpha_p \times DNI \times \cos(\theta) + \Psi_p \times DHI \quad (6)$$

$$GHI_{\text{Driving Mode}} = \alpha_d \times DNI \times \cos(\theta) + \Psi_d \times DHI \quad (7)$$

Where α and ψ are the shadow factor and sky clearness factor respectively. The α factor is vary between 0 and 1 and changes with time and depend on weather, surroundings, and locations. While, ψ is already included in the collected DHI values.

PV Position

GHI reaches on-board PV module depending on the tilt and azimuth angles of PV installation. In general, for both fixed ground mounted and roof-top PV applications, the optimum tilt angle is around the latitude of the geographical location, with the PV face (azimuth angle) to the south or north direction. For on-board PV use in vehicle applications, the module can face any direction in both parking and driving modes. Our results show that in such case, the optimum tilt angle is horizontal when PV module is fixed; this also eliminates any problems that may arise due to aerodynamics. However, if the PV module(s) are placed on a curved vehicle surface, different PV cells (or modules) will have different angles of incidence (θ) with respect to the sun, and I will be different for each module. If these modules

are connected in series, some of them must work with I not equal to I_{mp} . Consequently, net I for the PV module series will be the lowest I value, and a power mismatch problem will occur. DNI depends on (θ), and the power mismatch between the modules will be related to the difference between these different angles of incidence.

Two PV modules placed on a curved vehicle surface are shown in Figure 4. Angles of incidence of the PV modules 1 and 2 are θ_1 and θ_2 respectively. Power mismatch between the two modules is calculated using Equation (8). Assume that the curvature of the vehicle surface between the two regions where the two PV modules are installed, introduces a difference in incidence angles of less than 10° . If the sun is perpendicular to module 1 ($\theta_1 = 0^\circ$), power mismatch losses will be minor ($\sim < 1.52\%$). However, if $\theta_1 = 50^\circ$ (i.e. It is significant), then the power mismatch loss is around 14.3% (i.e. Power mismatch loss is also significant). Ideally, both the PV modules should be as parallel as possible.

$$\text{Mismatch loss} = |\cos(\theta_1 \cdot \pi / 180) - \cos(\theta_2 \cdot \pi / 180)| \times 100\% \quad (8)$$

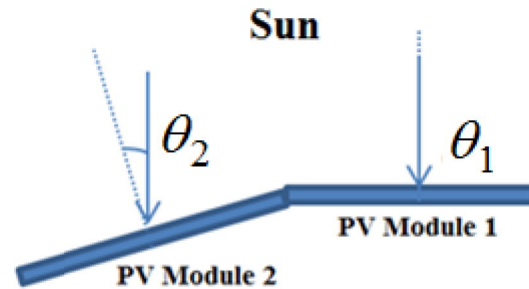


Figure 4. Angling PV on Vehicle Surface

Energy Storage and Vehicle Energy at Wheels

Energy demand at the wheels (E_w) for a given driving cycle and given vehicle, assuming the road grade to be zero, is calculated using Equation (9).

$$E_w = \frac{1}{2} \cdot \rho_a \cdot C_d \cdot A_f \cdot \int_{\text{Cycle}} v^3 dt + M_v \cdot g \cdot C_r \cdot \int_{\text{Cycle}} v dt + 1.1 \cdot M_v \cdot \int_{\text{Cycle}} v \frac{dv}{dt} dt \quad (9)$$

Energy generated by the PV module is stored using Li-ion polymer battery, about which full specifications and analysis are detailed elsewhere [19]. The slightly higher expected voltage of the PV module permits the use of the more efficient step-down DC-DC configuration. Equations (10), (11), (12) are used to calculate the solar energy-to-battery charging efficiency [20]. Charging efficiency is optimized when PV voltage is slightly higher than battery voltage. Optimum ratio V_{mp} to the battery voltage is equal to 1.029 and provides the best charging efficiency.

$$\text{Eff}(\%) = \left(\frac{\text{Avg. Voltage}(V) \times \text{Charge Increase}(Ah)}{\text{Avg. Solar Irrad.}(W/m^2) \times \text{PV Area}(m^2)} \right) \times \frac{\text{Battery Chrg. Eff.}(\%)}{\text{Time Interval}(hr)}$$

$$\text{Charge Increase} = \text{Current} \times \text{Time} \quad (11)$$

$$\eta = \frac{\int_{I < 0} (E_0 \cdot I) dt}{\int_{I < 0} (V \cdot I) dt} \quad (12)$$

Total energy stored (in kWh) for varying time and varying PV installation areas in the battery at Phoenix, AZ is shown in Figure 5. Here, approximately 0.421 kWh of stored energy is available in the battery at noon with a PV installation area of 2.5 m² and solar efficiency at STC that is equal to 20%. Total estimated energy stored in the battery using an assumed PV module (area = 3.26 m²) represents the daily energy generation equal to 4.81 kWh in June in Phoenix, AZ and 1.036 kWh in December in Boston, MA (see Appendix Table 1 for estimation of stored energy at different times).

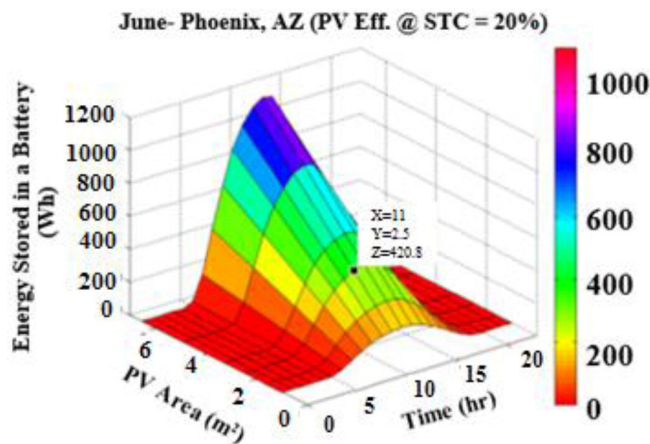


Figure 5. Energy stored in battery in June in Phoenix, AZ

RELATION OF CAFE STANDARDS WITH PV INSTALLATION SURFACE AREA

CAFE target, based on the vehicle footprint and PV output, depends on the installation area - typically the vehicle surface. We present in detail how we correlate the projected vehicle surface area with the 2020 and 2025 CAFE standards to determine the PV installation area required for these CAFE targets. Eight 2014-model vehicles with varying sizes are used: i) a two-seater car (Smart Fortwo), ii) a mini-compact car (Fiat 500e), iii) two sub-compact cars (Chevrolet Spark EV and Mitsubishi i-MiEV), iv) a compact size vehicle (Ford Focus), v) a mid-size vehicle (Nissan Leaf), vi) a large-size vehicle (Tesla Motor S), and vii) a small station wagon (Honda Fit). CAFE standard curves up to 2025 for passenger cars are provided in Figure 6 [1]. While x-axis represents the vehicle footprint in square feet (ft²), vehicle footprint is defined as the area consisting of the vehicle's wheelbase multiplied by the average track width.

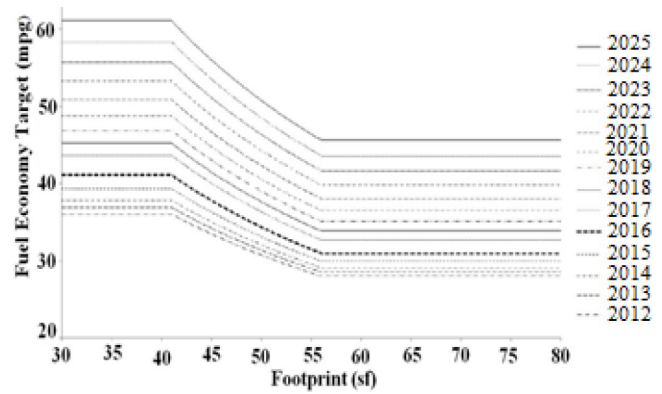


Figure 6. CAFE (MPG) Standard Curves for Passenger Cars [1], edited for clearness

CAFE target (MPG) curves for years 2020 and 2025 can be re-written as a criterion (13).

ft / MPG	CAFE 2020	CAFE 2025
$ft \leq 3.8 \text{ m}^2$	49	61
$3.8 \text{ m}^2 < ft < 5.1 \text{ m}^2$	$-0.93 \cdot ft^2 + 87.07$	$-1.07 \cdot ft^2 + 104.93$
$ft \geq 5.1 \text{ m}^2$	36	46

(13)

Where ft is in square feet .

Correlation between the reported values of vehicles' footprints and the projected horizontal surface areas of the eight selected vehicles is shown in Figure 7. Projected horizontal surface area for each vehicle is calculated based on the length and the width of the concerned vehicle. The predicted relationship (Equation 14) shows a linear relationship with R² equal to 0.9637, which is too high.

$$\text{Predicted Projected Horizontal Area} = 2.28 \times ft - 1.56 \quad (14)$$

Where, ft and predicted projected horizontal area are in square meters (m²).

The maximum error between the actual and predicted values of projected horizontal surface areas is found in the case of I-MiEV and Ford Focus vehicles - about 0.75 m² and 0.32 m² respectively - while for most other vehicles, the error is less than 0.1 m². The relation between the projected horizontal surface areas of vehicles and their CAFE targets in 2020 and 2025 is expressed using the criterion (15).

	CAFE in 2020	CAFE in 2025
$HS \leq 7.1 \text{ m}^2$	49	61
$7.1 \text{ m}^2 < HS < 10 \text{ m}^2$	36 - 49	46 - 61
$HS \geq 10 \text{ m}^2$	36	46

(15)