Impact of Photovoltaics-powered Vehicles

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Abstract

Development of high-efficiency solar cell modules and new application fields such as PV (Photovoltaics)-powered vehicles are significant for the further development of PV and the creation of new clean energy infrastructure based on PV. In this paper, analytical results for impact of high-efficiency solar cell modules on increasing driving distance, reducing CO_2 emission and saving charging cost of electric vehicles by PV-powered vehicles are presented. Because the Si tandem solar cells are expected to have significant potential for PV-powered vehicle applications, potentials of high-efficiency of Si tandem solar cells and driving distance of vehicles installed with Si tandem solar cells are also analyzed. The III-V/Si 3-junction solar cell modules with more than 35% have potential of driving distance of more than 30 km/day average and more than 50 km/day on a clear day.

Keywords: vehicle applications, high-efficiency, driving distance, CO_2 emission reduction, tandem solar cells and modules,

1. Introduction

Development of the PV(photovoltaics)-powered vehicleis (Yamaguchi et al., 2017a, NEDO, 2018, Rodriguez et al., 2019, Yamaguchi et al., 2020, Yamaguchi et al., 2021) is desirable and very imortant in order to creat new clean energy soceity. In order to enhance recognizing the PV-powered electric vehicles (PV-EV) as major clean vehicles and to create clean energy society based on PV, clarifying values of PV-EV and development of high-efficiency, low-cost, light-weight, 3-demensional curved and colorful solar cell modules and other technologies are necessary. This paper presents the importance of developing high-efficiency solar cell modules, especially Si tandem solar cells for PV-powered vehicles. In this paper, analytical results for effectiveness of high-efficiency Si tandem solar cell modules from point-views of driving distance, reduction in CO_2 emission and saving EV charging cost are shown.

2. Analysis for high-efficiency Impact on driving distance of PV-powered vehicles

Solar cell module efficiency impact on driving distance of PV-powered vehicles (PV-EV) was calculated. In the calculations, the charging system efficiency of 73.9% (Masuda et al. 2017) composing of cell temperature correction, maximum power point tracking, DC/DC conversion, and DC charging were assumed. Figure 1 shows calculated driving distance of PV-powered vehicles in the case of electric mileage of 9.35 km/kWh and solar irradiance 4kWh/m^2/day as a function of PV module nominal power in comparison with practical data for Toyota Prius 2019 (Yamaguchi et al., 2021), Toyota Prius 2017 (Yamaguchi et al., 2021), and Sono Motor Sion (Sono Motors). The Toyota Prius 2019 (demonstration car) (Yamaguchi et al., 2021) installed with about 30.9% efficiency module and output power of 860W has shown 29.9km/day driving distance at solar irradiance of 4.1kWh/m^2/day. On the other hands, the Sono Motor Sion (Sono Motors) installed 20-22% efficiency module has shown 15.3km/day average (solar irradiance of 3.84kW/m^2/day). It is clear that the higher-efficiency solar cell modules are promising for realizing the longer driving distance as shown in Fig. 1.

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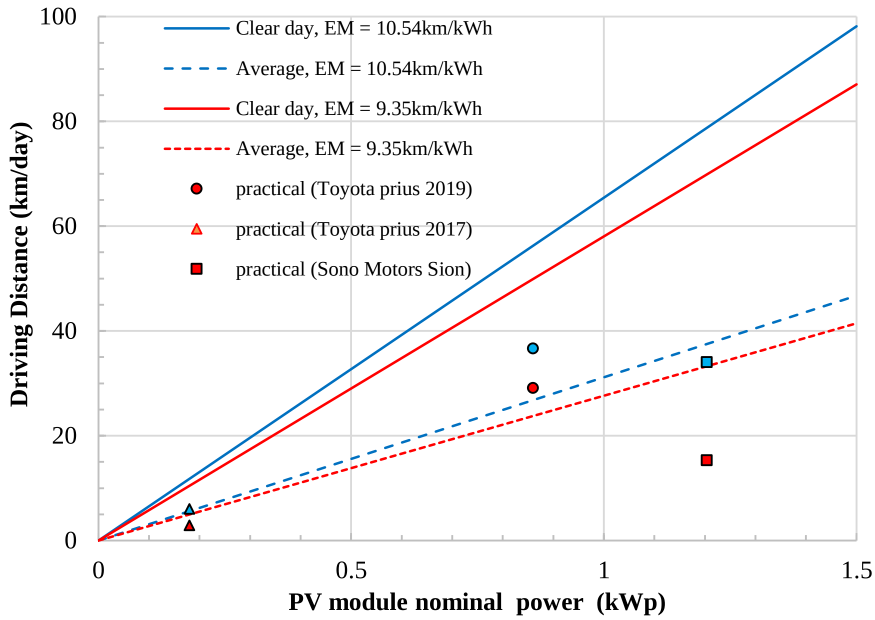

Fig. 1: Calculated driving distance of PV-powered vehicles in the case of electric mileage of 9.35 km/kWh and solar irradiance 4kWh/m^2/day as a function of PV module nominal power in comparison with practical data for Toyota Prius 2019, Toyota Prius 2017 and Sono Motor Sion. Blue colour plots show clear day data and red colour plots shows average driving distance.

3. Analysis for high-efficiency impact on CO_2 emission reduction by PV-EV

Effects of introduction of high-efficiency solar cell modules into EVs upon reduction in CO_2 emission were analysed. Average CO_2 emission intensity CI_{EV} for EVs is reported to be 462 g-CO_2 e/kWh (Ministry of the Environment). EV usage CO_2 emission CE_{EV} is expressed by

$$CE_{EV}[\text{g-}CO_2\text{ e/km}] = CI_{EV}[\text{g-}CO_2\text{ e/Wh}]EC_{EV}[\text{Wh/km}]) = CI_{EV}[\text{g-}CO_2\text{ e/Wh}]/EM[\text{km/Wh}]), \text{(eq. 1)}$$

where EC_{EV} is the EV energy consumption and EM is the electric mileage. On the other hands, CO_2 emission $CE_{PV\text{-}production}$ for PV-production is thought to be given by

$$CE_{PV\text{-}production}[\text{g-}CO_2\text{ e/km}] = P_{pv}[\text{W}]CI_{PV}[\text{g-}CO_2\text{ e/W}]/(DD\text{ [km/day]}\tau_{PV}\text{ [years]}), \text{(eq. 2)}$$

where P_{pv} is the module output power, CI_{PV} is the carbon intensity per unit W, DD is the driving distance, and τ_{PV} is the lifetime for PV modules. In this study, 1,008 g-CO_2 e/W was assumed as CI_{PV} according to the reference (Kanz et al., 2020) and 15 years were assumed as τ_{PV} because of PV-powered vehicle applications. The PV-EV usage CO_2 emission $CE_{PV\text{-}V}$ is expressed by

$$CE_{PV\text{-}EV}[\text{g-}CO_2\text{ e/km}] = CE_{EV}[\text{g-}CO_2\text{ e/km}] + CE_{PV\text{-}production}[\text{g-}CO_2\text{ e/km}]. \text{(eq. 3)}$$

Tendency for cumulative frequency CF of passenger cars in Japan (Hara et al., 2016) as a function of daily mileage was approximated by the following equation:

$$CF = 0.9\{1\text{-EXP}(-DD[\text{km/day}]/20)\}/0.1\{1\text{-EXP}(-DD[\text{km/day}]/200\}. \text{ (eq. 4)}$$

As shown in Section 2, driving distance DD was estimated by using the following equation:

$$DD[\text{km/day}] = SI[\text{kWh/m}^2\text{/day}]PR*\eta[\%]*0.01A\ [\text{m}^2]EM[\text{km/kWh}], \text{(eq. 5)}$$

where SI is the solar irradiance, PR the performance ratio of PV system and 0.739 [6] was used as the PR in this case, A is the area of solar cell module and 3 m^2 was used as A this time, and EM is the electric mileage. In the calculation, sharing ration of EV mode and PV mode for PV-EV was estimated by driving distance DD and eqs 1 – 5.

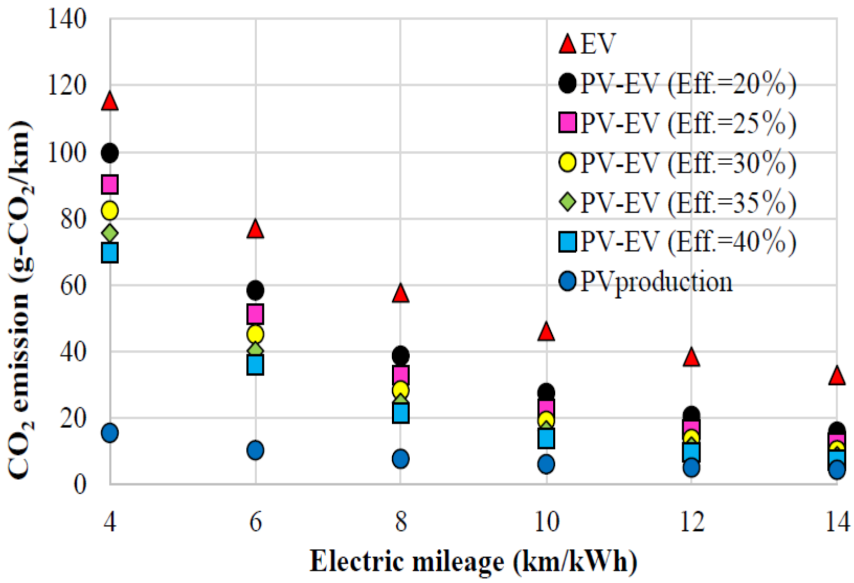

Fig. 2: Calculated results for CO_2 emission of PV-powered electric vehicles (PV-EV) installed with solar cell modules with different efficiencies as a function of electric mileage in comparison with those of electric vehicles (EV) and PV production.

Figure 2 shows calculated results for CO_2 emission of PV-EV installed with solar cell modules with different efficiencies as a function of electric mileage in comparison with those of EV and PV production. It is clear in Figure 2 that the PV-EV installed with the higher efficiency solar cell modules has great potential of reduction in CO_2 emission. 55% - 73% CO2 reduction will be realized by using the PV-powered vehicles with electric mileage of 10km/kWh.

4. Analysis for high-efficiency impact on EV charging cost saving by PV-EV

Electricity cost saving for EV charging by usage of PV was analysed in this study. EV energy consumption EC is given by

EC [kWh/year] = DD [km/year]/EM [km/kWh]. (eq. 6)

Charging electricity cost CC of EV charging is given by

CC [$/year] = EC [kWh/year]* EP [$/kWh], (eq. 7)

where EP is the household electricity and is $0.2/kWh in Japan in 2020 (Global Petrol Prices). PV-EV cost saving $\triangle CS_{PV\text{-}EV}$ was calculated by using the following equation

$\triangle CS_{PV\text{-}EV}$ [$/year] = $-\triangle E_{grid}$ [kWh/year]*EP [$/kWh]. (eq. 8)

In the similar way with analytical procedure described in Section 3, effectiveness of high-efficiency solar cell modules for cost saving of EV charging was analysed. By using eq. 4 for tendency for cumulative frequency CF of passenger cars in Japan as a function of daily mileage, charging possibility of PV-powered vehicles was calculated. Cost saving for charging of EV was calculated by considering reduction in charging frequency due to usage of PV and using eq. 8.

Figure 3 shows calculated results for charging electricity cost of EV and PV-EV as a function of electric millage by assuming 30 km/day as average daily driving distance. The results show effectiveness of high-efficiency solar cell modules for charging electricity cost saving of electric vehicles. For example, electricity cost saving is $254.1/year for 40% module and $149.1/year for 20% module in the case of electric mileage of 4 km/kWh, $167.2/year for 40% module and $117.8/year for 20% module in the case of electric mileage of 10 km/kWh.

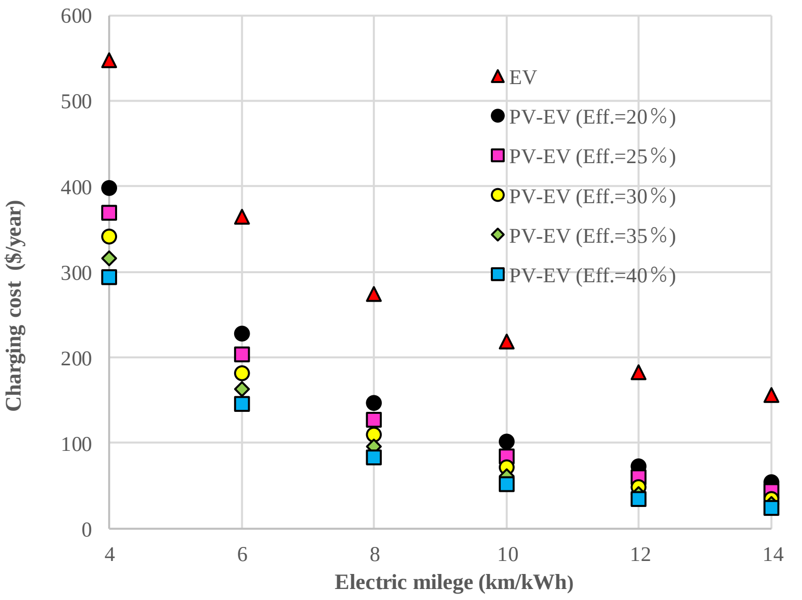

Fig. 3: Calculated results for charging electricity cost of EV and PV-EV as a function of electric mileage by assuming 30 km/day as average daily driving distance.

5. Analysis for driving distance of vehicles powered by Si tandem solar cells

As described above, the higher-efficiency solar cell modules have great potential for the longer driving distance, reduction in CO_2 emission and saving charging cost for electric vehicles. However, cost reduction of solar cell modules is also very important for attractive PV-powered vehicles. The Si-based tandem cells (Yamaguchi et al., 2018a, Essig et al., 2017) that combine Si with other materials such as III-V compound, II-VI compound, perovskite chalcopyrite, and so forth are desirable for realizing super high-efficiency and low cost. The Si tandem solar cells have been receiving considerable attention because of its potentials.

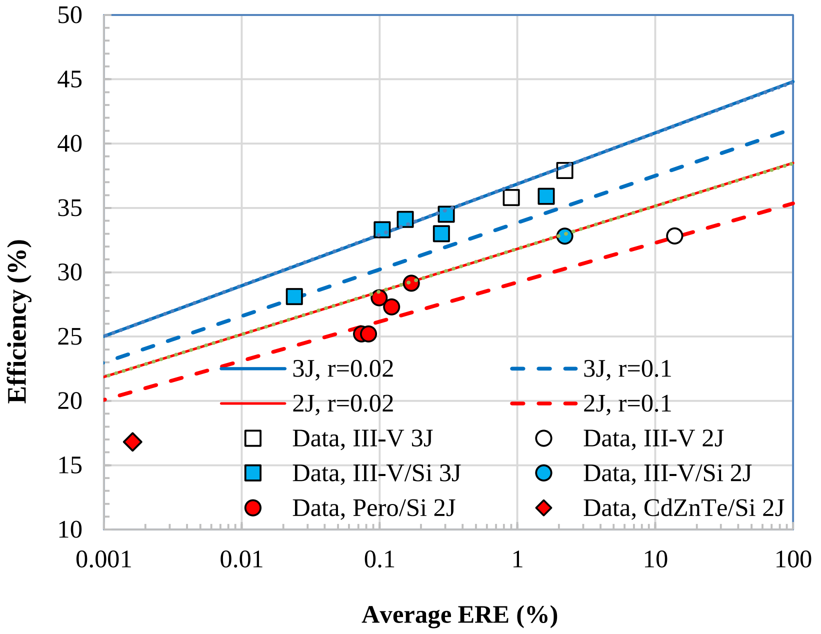

Fig. 4: Calculated 1-sun efficiency of III-V/Si triple-junction including our results III-V/Si and dual-junction tandem solar cells and perovskite/Si dual-junction tandem solar cells as a function of average external radiative efficiency (ERE) and resistance loss $_s$ + 1/r_{ss}. White rectangular shows InGaP/GaAs/InGaAs triple-junction tandem solar cells.

Previously, we have analyzed the efficiency potential of various solar cells by using our analytical procedure (Yamaguchi et al., 2017b, 2018c, 2018c). In the analysis for efficiency potential of Si tandem solar cells, the similar method and parameters reported in our previous papers (Yamaguchi et al., 2017b, 2018c, 2018c) were used. Figute 4 shows calculated 1-sun efficiency of III-V/Si triple-junction including our results and III-V/Si dual-junction tandem solar cells and perovskite/Si dual-junction tandem solar cells as a function of average external radiative efficiency (ERE) and resistance loss $r_s + 1/r_{ss}$. White rectangular and circle plots show InGaP/GaAs/InGaAs triple-junction and InGaP/GaAs dual-junction tandem solar cells.

Previously, we have achieved 28.2% efficiency (0.95 -cm^2 da) (Yamaguchi et al., 2018a, 2016a, 2016b) in 2016, and Sharp demonstrated 33% (Takamoto et al., 2017) (3.604-cm^2 ap) in 2017, with mechanically stacked InGaP/GaAs/Si 3-junction solar cells. At present, the III-V/Si 3-junction and 2-junction tandem solar cells have shown higher efficiency with 35.9% (Essig et al., 2017) (1.002-cm^2 da) and 32.8% (Essig et al., 2017) (1.003-cm^2 da) compared to perovskite/Si 2-junction tandem solar cells with efficiencies of 29.15% (1.030-cm^2 da) (Al-Ashouri et al., 2020) and CdZnTe/Si 2-junction tandem solar cell with an efficiency of 16.8% (0.126-cm^2 mesa area) (Cormody et al., 2010). Such an efficiency difference is thought to be a difference in material quality. For example, the external radiative efficiency values (ERE) are 1-2.2% for III-V/Si tandem cells, 0.1-0.17 % for perovskite/Si tandem cells, 0.0016 % for CdZnTe/Si tandem cells. Therefore, a material quality is critical for further improvements in the performance of Si tandem solar cells. Although efficiency (35.9%) (Essig et al., 2017) of 4-terminal mechanical stacked InGaP/GaAs/Si 3-junction tandem solar cells is close to that of InGaP/GaAs/InGaAs 3-junction cells (37.9% for 1.047-cm^2 ap) (Sasaki et al., 2013), resistance loss is higher as shown in Figure 4. Resistance loss for the perovskite/Si tandem cells and CdZnTe/Si tandem cells are much higher compared to the III-V/Si tandem solar cells as s shown in Figure 4. The 3-junction and 2-junction Si tandem solar cells have an efficiency potential of 42% and 36%, respectively.

Figure 5 shows calculated results for driving distance of vehicles powered by perovskite/Si 2-junction, III-V/Si 2-junction and III-V/Si 3-juncttion tandem solar cells and III-V 3-junction tandem solar cells and module as a function of module efficiency and temperature coefficient (TC) in comparison with estimated values of vehicles powered by perovskite/Si 2-junction, II-V/Si 2-junction and III-V/Si 3-juncttion tandem solar cells and III-V 3-junction tandem solar cells and module and actual driving distance calibrated of the Prius 2019 (Yamaguchi et al., 2021) powered by III-V 3-junction solar cell module and the Sono Motors Sion (Sono Motors) powered by back-contact Si solar cell module. The III-V/Si 3-junction solar cell modules have potential of driving distance of 30 km/day average and more than 50 km/day on a clear day.

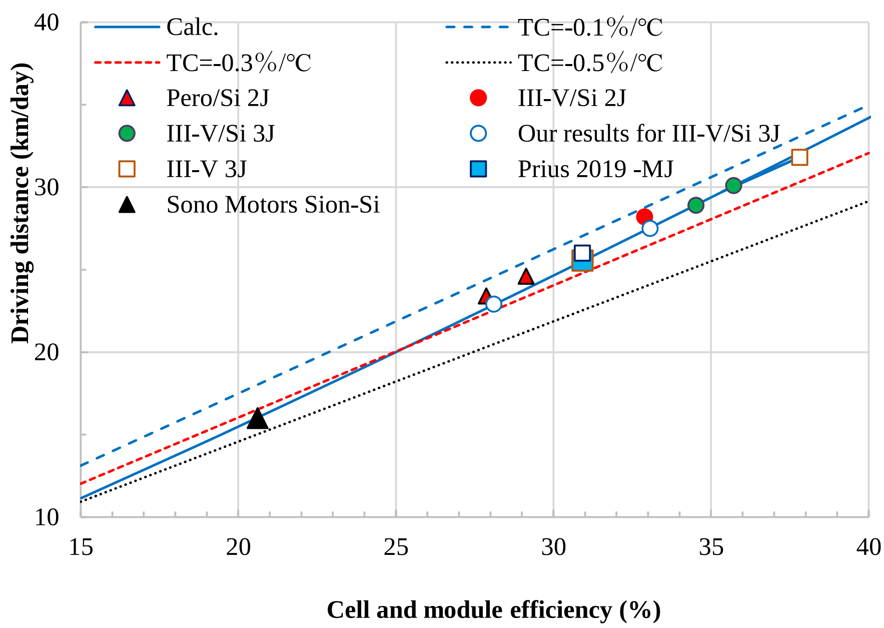

Fig. 5: Calculated results for driving distance of vehicles powered by perovskite/Si 2-junction, III-V/Si 2-junction and III-V/Si 3-juncttion tandem solar cells and III-V 3-junction tandem solar cells and module as a function of cell and module efficiency and temperature coefficient (TC) in comparison with estimated values of vehicles powered by perovskite/Si 2-junction, III-V/Si 2-junction and III-V/Si 3-juncttion tandem solar cells and III-V 3-junction tandem solar cells and module and actual driving distance calibrated of the Prius 2019 [1] powered by 3-junction solar cell module

6. Summary

The development of PV-powered vehicle applications is desirable and very important for reducing CO_2 emission of vehicles and creation of mobility society.

This paper presented importance of developing PV-powered vehicles from points-views of re-duction in CO2 emission, charging cost reduction for electric vehicles and reducing storage capacity of PV-powered electric vehicles.

This paper has shown that reduction of 55% - 73% CO2 emission will be realized by using the PV-powered vehicles with electric mileage of 10km/kWh and the higher-efficiency solar cell modules have possibility of great contribution to CO2 emission reduction in the PV-powered vehicles.

The results also have shown the effectiveness of high-efficiency solar cell modules for charging electricity cost saving of electric vehicles. For example, electricity cost saving is $254.1/year for 40% module and $149.1/year for 20% module in the case of electric mileage of 4 km/kWh, $167.2/year for 40% module and $117.8/year for 20% module in the case of electric mileage of 10 km/kWh.

In this paper, analytical results for effectiveness of high-efficiency solar cell modules from point-views of driving distance, reduction in CO2 emission and saving EV charging cost were shown. The Si tandem solar cells are expected to have significant potential for PV-powered vehicle applications because of high efficiency with efficiencies of more than 42% under 1-sun AM1.5 G, lightweight and low-cost potential. It is summarized that the III-V/Si 3-junction solar cell modules with module efficiency of more than 35% have potential of driving distance of more than 30 km/day average and more than 50 km/day on a clear day.

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