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Public road driving tests of Toyota Prius equipped with high-efficiency III-V triple-junction PV modules

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Abstract. This paper presents the measurement results of public road tests of a solar-powered plug-in hybrid electric vehicle that is equipped with PV modules (2–9) that have a rated-output power of 860 W. The vehicle-integrated PV modules consist of III-V-based triple-junction solar cells with an average conversion efficiency of approximately 34%. The measurement results indicate that the number of plug-in charging cycles can be reduced significantly by integrated PV modules, which increase the convenience of use of the battery-based vehicles. Even energy self-sufficiency was achieved for the neighborhood driving pattern. Further, in Aichi prefecture, Japan, the annual solar-powered driving range reached 6211 km in the year 2021. As the average annual driving range of passenger cars in Japan is approximately 10,000 km, it was experimentally confirmed that CO_2 emission from passenger cars in Japan can be reduced by approximately 62% by installing vehicle-integrated PV modules. Future direction for PV modules and solar powered vehicles is also discussed.

Keywords: vehicle-integrated photovoltaics / III-V solar cell / public road test / solar-powered vehicle

1 Introduction

In recent years, countries around the world have stepped up their efforts to reduce CO_2 emission in response to global warming. It is reported that CO_2 emission from the transportation sector accounts for approximately 24% of the world's total emission, of which approximately 44% are produced from passenger cars [1,2]. Therefore, reducing CO_2 emission produced by passenger cars is essential to realize a carbon-neutral society in the future. To reduce the CO_2 emission from passenger cars, automobile companies are accelerating the development of several environment-friendly vehicles such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), fuel-cell electric vehicles (FCEVs), and battery electric vehicles (BEVs). Environment-friendly vehicles, particularly PHEVs and BEVs, are equipped with large-capacity batteries, which makes them compatible with renewable energy. Among them, PV modules that have a plate-like structure are suitable for vehicle-integrated use [3,4].

In this study, we developed a PHEV based on the commercially available model (Prius PHEV) equipped with high-efficimcy III-V compound 3-junction solar cells with a conversion efficiency of approximately 34% that have a rated-output of 860 W and 8.8-kWh batteries to experimentally confirm the benefits of vehicle-integrated PV modules for passenger cars. The results of the public road driving tests performed on the solar-powered PHEV are presented. In addition, impacts of high-efficiency PV modules upon driving distance, reduction in CO2 emission and charging cost saving of solar-powered electric vehicles are shown in this paper.

2 Outline of demonstration car and test driving

We installed PV modules based on III-V compound triple-junction solar cells with an average conversion efficiency of approximately 34% on the roof, hood, and rear hatch door of the PHEV Prius (demonstration car). Figure 1 shows the photographs of the developed solar-powered demonstration car.

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Fig. 1. Photographs of the solar-powered car equipped with III-V triple-junction PV modules.

Table 1. Comparison of the demonstration car developed and mass production model.

Model	Demonstration car	Mass production (~2017)
Photo		
Solar cell	III-V based 3J (34%)	c-Si (22.5%)
Installed area	Roof, hood, and back door	Roof
Output power	860 W	180 W
Battery capacity	8.8 kWh	8.8 kWh

Table 1 shows verification for the demonstration car developed in comparson with mass production model shipped in 2017 [5]. The three PV modules are installed on the engine hood, roof, and back door as shown in Figure 1 and Table 1. The modules consist of 288, 576, and 306 cells, respectively, for the hood, roof, and back door with MPP tracking applied individually. The total rated-output power of the integrated solar cell module reached approximately 860 W, which is 4.8 times higher in comparison with the commercial model Prius PHEV [5], which is equipped with a crystalline Si hetero-junction solar cell module with a conversion efficiency of 20% and rated-output power of approximately 180 W. Installation area of 3-junctuion solar cell modules is about 2.8 m^2. The output power is also the nominal output power measured under standard condition. The demonstration car is equipped with an 8.8-kWh battery, which can store the electricity generated by the integrated PV modules. We have also compared the results of the study with a Nissan Van demonstration vehicle, which is equipped with modules consisting of 178 W (2 panels), 788 W (6 panels), and 187 W (2 panels), respectively, for the hood, roof, and back door [6]. The total rated output power of the integrated solar cell module reached approximately 1150 W. The Nissan demonstration car is equipped with a 40 kWh battery, which can store the electricity generated by the integrated PV modules. The electric millage (EM) of the Nissan demonstration is 6.6 km/kWh while the EM of the Toyota demonstration car is 9.35 km/kWh. 4 daily driving patterns of 5 km, 15 km, 50 km and 150 km were tested.

Public road driving tests have been conducted since 2019 using the demonstration car for the purpose of experimentally evaluating the effects of vehicle-integrated PV modules, namely, those of reducing CO_2 emission from passenger cars and improving convenience such as reducing the number of plug-in charging cycles. We used the three driving patterns which were randomly arranged every day during the public road tests. In each driving pattern, the car was driven two times a day and parked outdoors at other times. We measured the power generated by the modules, module temperature, irradiance, charged watt-hour, and driving data. Solar irradiation SI was the averaged measured data with eight Si based pyranometers (ML-02) which were attached on exterior of the demonstration car. The driving distance was calculated with the data of the measured generated power by the integrated PV modules and measured EM of the demonstration car.

Test drivings were carried out everyday by using the following 3 patters. Charging was carried out while parking. In driving pattern A, the car was driven on a highway and the total daily driving range was 70 km. In driving pattern B, driving around in the neighborhood, such as for daily shopping, pick-up/drop-off, and so on, was simulated, and the total daily driving range was 5 km. Commuting, with a total driving range of 15 km, was simulated in driving pattern C.

Table 2. Driving test condition of the Toyota Prius solar powered demonstration car.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tire	Studdles snow tires			Normal tire								Studdles Snow tires
Air conditioner	Heat 23 °C		OFF		Cool 25 °C					OFF		Heat
Ave. outdoor temp. (°C)	7.1	5.6	12.7	16.5	20.9	25.2	25.7	31.2	25.0	17.6	14.5	7.8

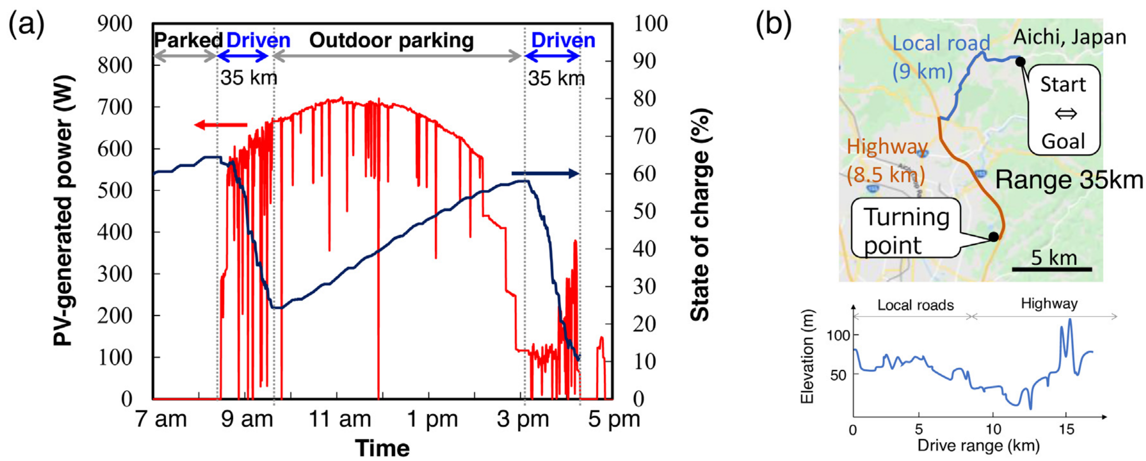

Fig. 2. (a) Measurement of power generated by the integrated PV modules and state of charge (SOC) of the battery as functions of time obtained in May 2020. (b) The driving route of pattern A.

The driving tests were conducted in mainly Tokyota city in Aichi prefecture, Japan, when the air-conditioner was turned on to simulate the actual usage environment of passenger cars as shown in Table 2. The temperature of the air-conditioner was fixed at 25 °C during summer (May–Sep) and 23 °C during winter (Dec–Feb) Studless snow tires were used from December to March and normal tires were used from April to October. Both the air-conditioning and tires can largely affect the electricity consumption rate of electric vehicles. Parking has been made with non-roof (open-air) parking.

3 Results and discussion

3.1 Single day analysis

Figure 2 shows the typical results of measurement of the power generated by the integrated PV modules and the state of charge (SOC) of the battery as a function of time and driving route measured with driving pattern A, which denotes a run of 35 km each in the morning and afternoon. An example for charging cycle is also shown in Figure 2.

The SOC dropped from 66% to 24% owing to the power consumed during the 35-km-long morning drive, but it was recovered to 58% through charging using the integrated PV modules during outdoor parking from 10 am to 3 pm. The amount of power generated by the integrated PV modules on the day of the measurement was measured to be approximately 3.2 kWh/day (4-2). Because the measured electric mileage for the demonstration car of the day was 11.5 km/kWh, the observed daily solar-powered driving range was 37 km. The results of the measurement indicate that the energy self-sufficient ratio was calculated to be 53% because the total distance driven during the day was 70 km and the solar-powered driving range was 37 km.

3.2 Self-sufficient ratio

Figure 3 shows the results of measurement of the energy self-sufficient (ES) ratio as a function of date from July 2020 to June 2021 for the driving patterns A, B, and C, respectively. Climate condition (average temperature = 16.9 °C, average DGHI = 4.02 kWh/m$^{2/}$day) tested in Aichi prefecture was the similar with the standard climate condition (average temperature = 17.0 °C), average DGHI = 4.06 kWh/m$^{2/}$day there [7]. Figure 3a indicates that the solar-powered driving range fluctuated significantly depending on the season, mainly owing to two reasons: difference in the (i) solar irradiance and (ii) EM (electric mileage) of the vehicle due to usage of air-conditioners and module temperature changes. The measured longest daily solar-powered driving range was 56 km/day (recorded on April 19, 2021) when both the power generation and EM were high, which is equivalent to an energy self-sufficient ratio of 80% for the driving pattern A. Figure 3b indicates that energy self-sufficiency driving, that is, driving without plug-in charging, can be achieved for neighborhood usage (driving pattern B), whereas

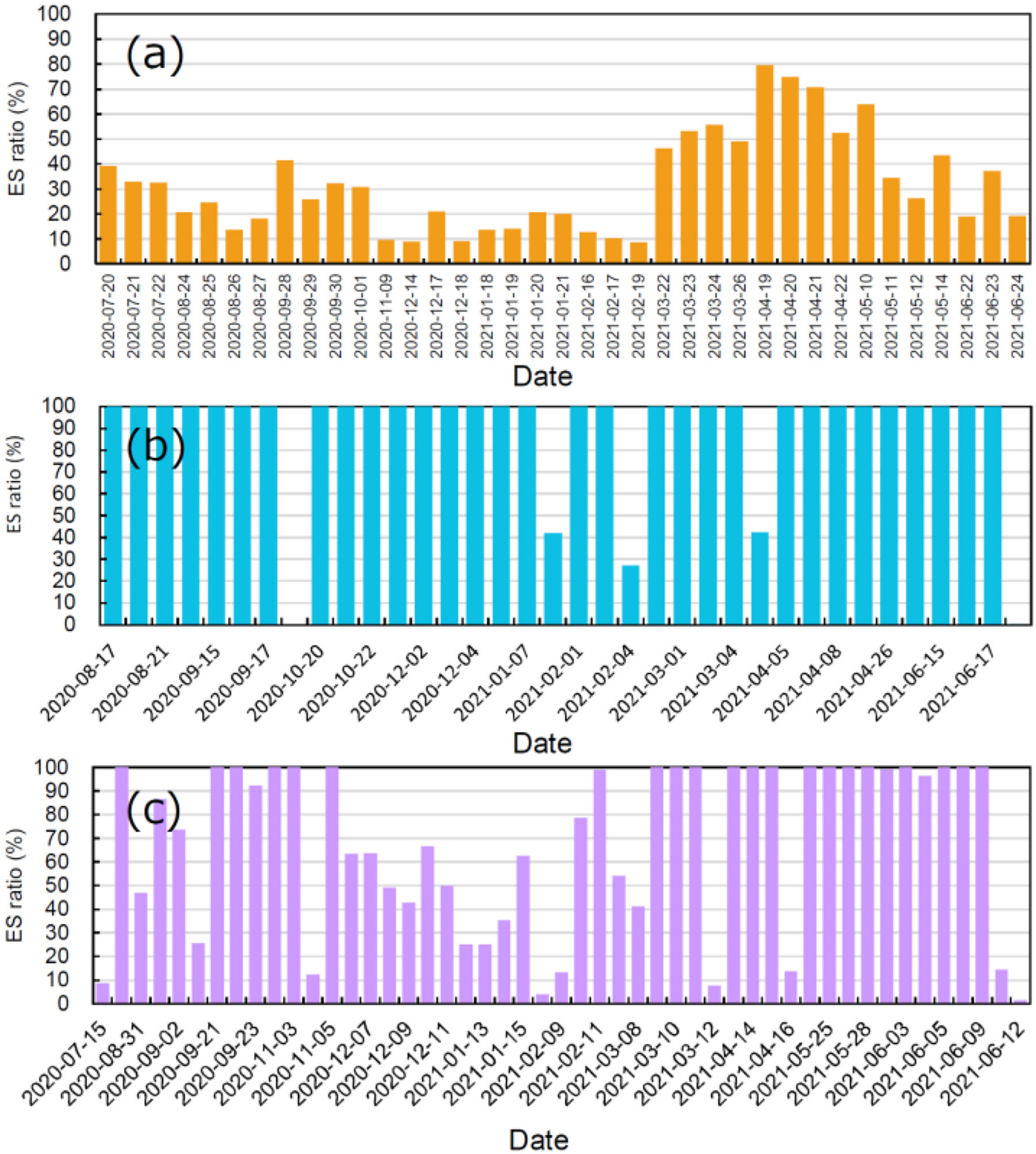

Fig. 3. Measured energy self-sufficient (ES) ratio as a function of date for driving patterns A (a), B (b), and C (c). The data were obtained from July 2020 to June 2021.

approximately half of the number of plug-in charging cycles can be avoided for the commute usage (driving pattern C) with the daily driving range of 15 km, as depicted in Figure 3c.

From the results of the measurement, we experimentally confirmed that installing the PV modules in electric passenger cars have a significant potential to reduce the number of plug-in charging cycles, which can improve the convenience of battery-based electric vehicles, such as PHEVs and BEVs, remarkably.

3.3 Annual driving range (3–6)

We then investigated the annual driving range powered by integrated PV modules. The power generated by the integrated PV modules is affected by various factors [8]. For example, it is affected by not only solar irradiance and the solar spectrum but also the direction the car is facing, partial shading, light reflected by the surrounding objects, and so on [9]. We found that there is good correlation between the daily global horizontal irradiance (DGHI) and

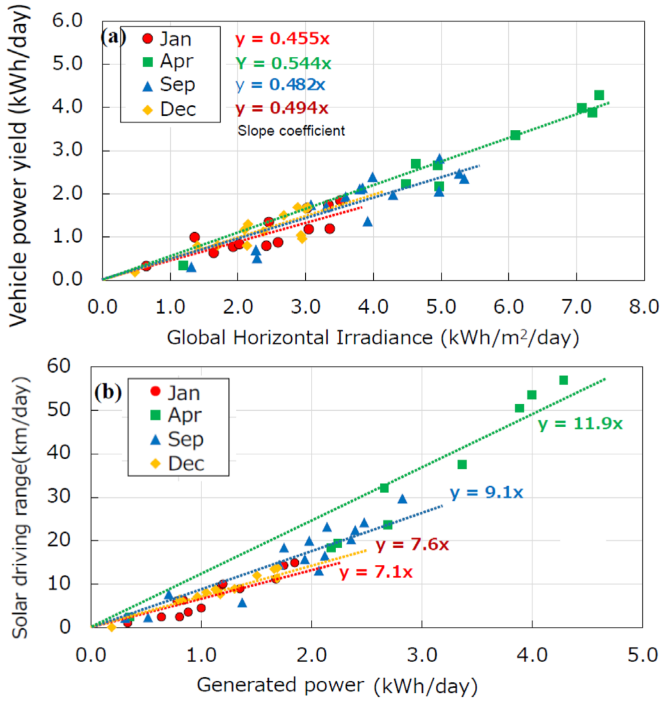

Fig. 4. (a) Measured generated power as a function of daily global horizontal irradiance (DGHI); (b) solar-powered driving range as a function of the power generated by the integrated PV modules.

daily generated power when it is plotted monthly, which is independent of the driving patterns, as depicted in Figure 4a but is depend upon partial shading and PV module temperature. The slope coefficients between the two factors (SC1) of each month were estimated to be between 0.28 (m^{-2}) and 0.58 (m^{-2}) (3–10), Temperature rise of PV modules and rain drops in the rainy season are thought to be as possible origins for large variation of the slope coefficient SC1.

Figure 4b depicts the solar-powered driving range as a function of power generated daily by the integrated PV modules. The results indicate that there is also a proportional relationship between the daily generated power and the daily solar driving range when it is plotted monthly. The estimated slope coefficients (SC2) for each month were found to fluctuate from 5.9 (km/kWh) in February to 12.0 (km/kWh) in April. The observed larger fluctuation compared to the slope coefficient between the DGHI and the daily generated power (Fig. 4a) is attributed mainly to the large fluctuation in the rate of electric power consumed for driving the car owing to a seasonal change in the outdoor temperature. Larger driving distance decrease of solar powered vehicles has been observed in the summer and winter. As discussed below, usage of air-conditioners is thought to be as major power loss of the solar-EV.

Table 3 shows calculated results of annual driving range of Toyota Prius solar powered demonstration car driven in Nagoya, Japan. The proportional constant 1 shows ratio of energy yield to the GHI (global horizontal irradiation) and the proportional constant 2 shows ratio of driving range to energy yield.

We estimated the annual PV-powered driving range using the reported GHI (global horizontal irradiation) values [10] and calculated generated power. The highest cumulative amount of GHI in the month measured in Aichi prefecture, Japan, was 180.8 kWh/m^2 in August, whereas the lowest value was 77.5 kWh/m^2 in December. The annual solar-powered driving range estimated using the GHI values and slope coefficients was 6211 km. The average daily solar powered-driving distance of 17 km/day is lower than the daily driving range of 23.9 km/day estimated [9]. Since the maximum PV yield generated was measured around 4 kWh/day (below half of the battery capacity), the generated power could be used completely in almost all cases when the vehicle was driven during the day.

3.4 Power loss analysis

The authors have analyzed measured effects of temperature rise of Si modules [11], usage of air-conditioners [12] and partial shading [13] upon driving distance of SEV.

The daily driving distance (DD) [km/day] of solar-EV was calculated by the following equation:

$$\mathrm{DD} = \mathrm{DGHI} \times \mathrm{SE} \times P_{out} \times EM, \quad (1)$$

where DGHI [kwh/m^2/day] is the daily global horizontal irradiation, SE is the efficiency of the PV system, P_{out} [kW] is the output power of the solar cell module, and EM [km/kWh] is the electric mileage of the solar-EV. Power loss due to air-conditioning was determined from changes in electrical mileage EM using equation (1), 0.739 [3] as SE, 860 W as output power P_{out} and actual driving data.

Figure 5 shows monthly data for the electric millage EM for the Toyota Prius demonstration car and Nissan demonstration car. In the summer and winter, larger power loss of the Toyota Prius demonstration car has been observed although the Nissan demonstration car hasn't shown significant power loss. Reduction in electric mileage of the Toyota Prius demonstration car during one year of driving is mainly originated from usage of air-conditioner usage [12].

The following equations for power loss of vehicles due to usage of air-conditioner were derived from estimation of EM changes as a result of changes in driving distance as shown in our previous paper [12]. Power loss was calculated by using equation (2) for Nissan van demonstration car and (3) for Toyota Prius demonstration car (Comment 10) and maximum outside temperature T_{max}, respectively [12].

$$\mathrm{EM} = \mathrm{EM}_0(16 - T_{max}) \times (\pm 0.2)[\mathrm{km/kWh/°C}], \quad (2)$$

$$\mathrm{EM} = \mathrm{EM}_0(19 - T_{max}) \times (\pm 0.4)[\mathrm{km/kWh/°C}], \quad (3)$$

where EM_0 is the original EM of solar-EV in the case of no operation of air-conditioners. In the case of the Toyota Prius demonstration car, EM decreases from 9.35 km/kWh that is original value to 6.9 km/kWh that is average value (26% decrease) due to the usage of air-conditioners in Nagoya and power loss due to usage of air-conditioner is thought to be dependent upon equation (3) [12]. On the other hand, the decrease rate of EM from 6.62 km/kWh

Table 3. Calculated results of annual driving range of Toyota Prius solar powered demonstration car driven in Nagoya, Japan.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Slope coefficient 1 (GHI → Power yield)	0.45	0.58	0.52	0.50	0.49	0.37	0.46	0.28	0.48	0.46	0.44	0.49	
Slope coefficient 2 (Yield → Drive range)	6.85	5.91	10.04	11.97	11.19	9.46	9.96	6.89	9.07	10.05	9.33	7.58	
GHI(kWh/m^2/month)	78.3	98.0	130.0	170.8	169.6	144.1	105.9	180.8	115.8	102.4	93.3	77.5	
Generated power (kWh/month)	49.8	62.3	82.6	180.6	107.8	9.1.6	67.3	114.9	73.6	65.1	59.3	49.3	932.0
Solar driving range (km/month)	244	337	682	1031	934	501	482	343	507	476	383	290	6211

GHI was obtained from https://www.data.jma.go.jp/gmd/risk/obsdl/

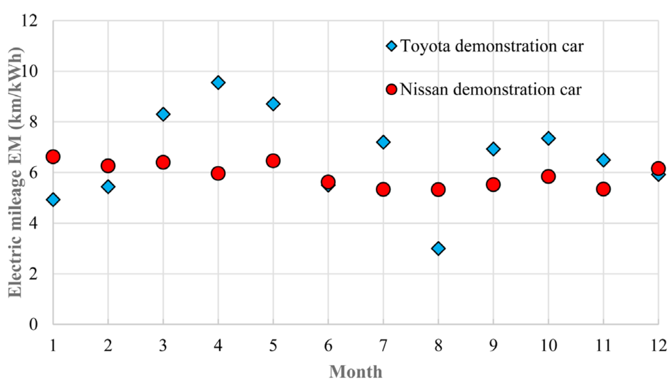

Fig. 5. Monthly data for electric mileage EM for the Toyota Prius demonstration car and Nissan demonstration car (revised).

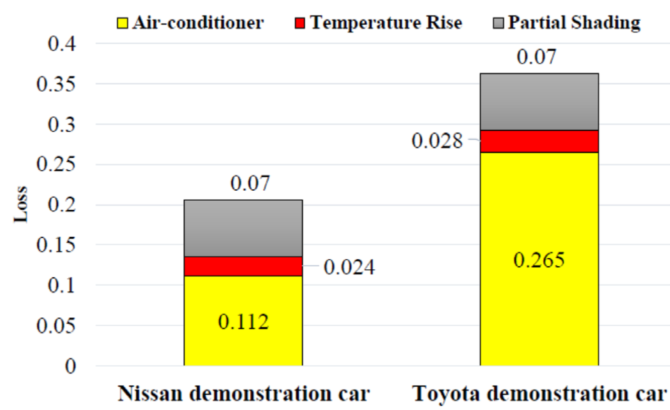

Fig. 6. Analytical results of various power losses of solar powered-vehicles according to test driving by Toyota and Nissan demonstration cars.

originally to 5.88 km/kWh that is average value (only 11% decrease) is lower in the case of the Nissan Van demonstration car in Yokohama and power loss due to usage of air-conditioner is thought to be dependent upon equation (2) [12]. Such a power is the similar with that of conventional EV [14] and is thought to be occurred in the usual solar-EV. (4-16) Less EM reduction in the case of the Nissan Van demonstration car is thought to be due to mild climate conditions in Yokohama and the drivers' intention for power saving [12]. Effects of air-conditioning on the driving range of electric vehicles for various driving modes have also been studied and 33% average decreases in driving range by air-conditioning have been reported [15]. 37.27% power loss of electric vehicles by using air-conditioning has also been reported [16]. The vehicle integrated PV modules are thought to be useful for heat shielding.

Figure 6 summarizes effects of various power losses upon driving distance of solar powered-vehicles in the Toyota and Nissan demonstration cars. Power loss due to temperature modules was reported by our previous papers [10,15]. Power loss due to partial shading was estimated by using vehicle/fixed point irradiation ratio as shown in the reference [13]. Power loss difference due to usage of air-conditioner depends on climate condition and driver intention [12].

3.5 Effectiveness of high-efficiency PV modules for solar-EV applications

Because the annual PV-powered driving range estimated using the DGHI values and slope coefficients, as presented in Table 2, was 6211 km and the average annual driving range of passenger cars in Japan is approximately 10,000 km, the CO_2 emission from passenger cars can be reduced by 62% by installing PV modules as shown in our previous paper [17]. The effectiveness of the introduction of high-efficiency PV modules into EVs upon reduction in CO_2 emission was reported by the authors [17]. Figure 7 shows the calculated results for reduction ratio of CO_2 emission of solar-powered EV installed with PV modules with different efficiencies as a function of electric mileage EM. It is clear in Figure 7 that the solar-powered EV installed with the higher efficiency PV modules have greater ability of reduction in CO_2 emission compared to EV without PV mmodule installation. Annual CO_2 emission reduction of EV with electric mileage EM of 10 km/kWh in Japan is estimated to be 188 kg CO_2-eq/year (46% CO_2 reduction), 255 kg CO_2-eq/year (63% reduction) and 295 kg CO_2-eq/year (73% CO_2 reduction)

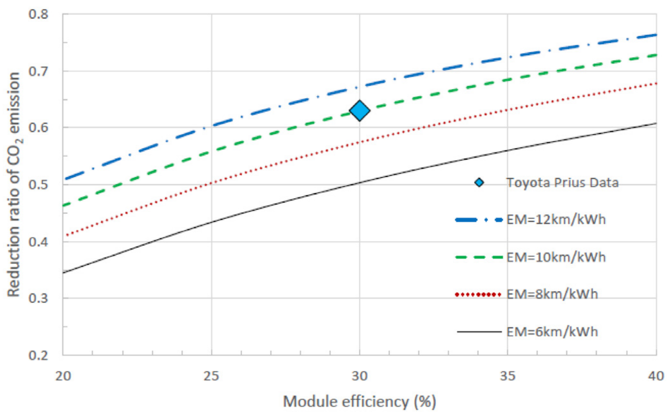

Fig. 7. Calculated results for reduction ratio of CO_2 emission of solar-powered EV installed with PV modules with different efficiencies as a function of electric mileage EM.

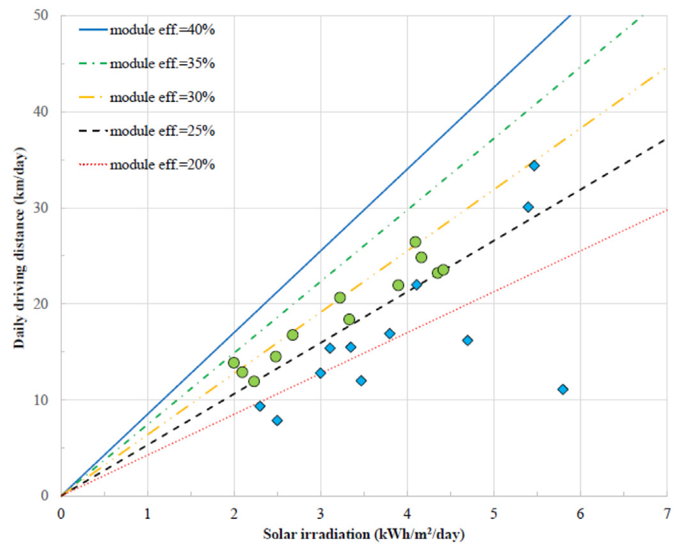

Fig. 8. Calculated results for solar irradiation dependence of daily driving distance of solar-powered EV as a function of module efficiency in comparison with test data of Toyota Prius demonstration car (blue dots) and Nissan demonstration car (green dots).

for solar cell module efficiency of 20%, 30% and 40%, respectively. The experimental results of the Toyota demonstration car which showed that the annual CO_2 emission reduction by 62% for a passenger car confirmed the validity of the calculated results [17]. Figure 7 suggests that from the view point of CO_2 emission reduction, the solar-power usage with the high conversion efficiency (>30%) is very effective for heavy vehicles which generally have low electric mileage such as vans, trucks and trailers [18].

In addition, approximately 33% of the passenger cars in Japan can be fully energy self-sufficiency when PV modules are installed. A report by the Ministry of Japan [19,20] showed that the average trip distance of passenger car in Japan is 24 km/day and approximately 70% of the passenger. car runs less than 30 km per day. Both the annual driving range and the percentage of fully energy-sufficiency cars can be increased by improving the charging efficiency of the integrated PV modules, which has not been optimized in the demonstration car yet.

Based on the results obtained from the public road driving tests that were conducted under driving conditions close to real usage, it was experimentally confirmed that the vehicle-integrated PV modules have significant potential to reduce CO_2 emission generated by the transport sector and improve the convenience of use of battery-based electric vehicles (PHEVs and BEVs). It is expected that solar-powered vehicles will play a critical role in a future carbon-neutral society.

The impact of high-efficiency solar cell module upon daily driving distance of solar powered vehicles was analyzed by calculating the daily drive distance by using equation (1) in order to discuss about future direction of PV modules. Figure 8 shows calculated results for solar irradiation dependence of daily driving distance of solar-powered EV as a function of module efficiency in comparison with test data of Toyota Prius demonstration car and Nissan demonstration car, Although daily driving distance for the Toyota Prius demonstration car fluctuates due to usage of air-conditioner, the Nissan Van demonstration car shows fewer fluctuations, Figure 8 suggests importance of high-efficiency PV modules in order to realize longer driving range and shows that high-efficiency PV modules with an efficiency of more than 35% have longer driving of more than 30 km/day average (4kWh/m2. day) and more than 50 km/day on clear day. In addition, higher efficiency PV modules have great potential for reduction in CO_2 emission as shown in Figure 7 and for electricity charging cost saving [21]. As shown in our previous paper [21], the electricity cost saving of solar-EV is \$167.2/year for a PV module with a conversion efficiency of 40% and \$117.8/year for a module with that of 20% in the case of an EM of 10 km/kWh.

In summary, solar-powered vehicle can reduce CO_2 emission charging cycle and cost saving However, usage of air-conditioners, temperature rise of PV modules and partial shading are major power losses. Development of high-efficiency, low-cost, highly reliable, 3-dimensional and colorful PV modules, and efficient battery management system and air-conditioners is very important for wide-spread deployment of solar powered vehicles. Further loss analysis, prediction of solar irradiation and power generation and feedback to car driving patters are necessary for improving performance of solar-EV.

The PV price estimated [EPE] are about \$30/W for Toyota Prius shipped in 2009 and \$12/W for the Toyota Prius PHV shipped in 2017, respectively. According to our [4] and NREL [22] cost analysis, high-speed deposition [23,24] and Si tandem solar cell modules [25] and increase in module production volume from 1 MW/year to more than 1 GW/year have great cost reduction potential of less than \$1/W. Flexible and light-weight PV modules are very attractive for solar-EV applications. Epitaxial lift-of technologies are one candidate for solar-EV applications because light weight solar cells have already been used for space [26].

4 Conclusion

A solar-powered PHEV that is equipped with PV modules that comprised of III-V triple-junction solar cells, its average conversion efficiency with approximately 34%, was developed. The total output power of the integrated PV modules was 860 W. Public road tests were conducted under three different driving patterns over the course of a year. The results of the tests indicated that the electric mileage of the solar-powered vehicle varied widely depending on the outside temperature, which affected the solar-powered driving range. The results of the measurement of the energy self-sufficient (ES) ratio indicated that the full energy self-sufficiency can be achieved for neighborhood usage, whereas approximately half of the number of the plug-in charging cycles can be avoided for the commute usage. In addition, an annual driving range of 6211 km could be achieved in Aichi prefecture, Japan, owing to power generation by the solar cell module. The results indicated that installing integrated PV modules can reduce the CO_2 emission from passenger cars by 62% annually and could improve the convenience of electric passenger cars. Future direction for PV modules and solar powered vehicles were also discussed.

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Conflicts of interest

The authors declared no conflict of interest.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author contribution statement

Conceptualization, T.N. and T.M., Methodology, T.N., Y.M. and M.Y., Validation, T.M., T.N., S.I. and M.Y., Formal Analysis, T.M., T.N., S.I. and M.Y., Module production, T.T., Investigation, all, Data Curation, all, Writing – Original Draft Preparation, T.M., Writing – Review & Editing, M.Y. and S.I., Visualization, T.M., S.I. and M.Y., Supervision, M.Y.; Project Administration, T.T and K.N.; Funding Acquisition, T.T. and K. N.

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