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Development of high-efficiency and low-cost solar cells for PV-powered vehicles application

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Abstract

Development of high-efficiency solar cell modules and new application fields are significant for the further development of photovoltaics (PVs) and the creation of new clean energy infrastructure based on PV. Notably, the development of PV-powered vehicle applications is desirable and very important for this end. According to the NEDO's Interim Report "PV-Powered Vehicle Strategy Committee," a new broader PV markets with more than 10 GW and 50 GW in 2030 and 2040, respectively, are expected to be established when PV-powered vehicles are developed. Cumulative PV capacity for PV-powered vehicles will be 50 GW and 0.4 TW in 2030 and 2040, respectively. This paper presents impacts on efficiency and cost for PV-powered vehicles. According to our survey, the use of more than 30% of high-efficiency PV enables 30 km per day driving without external charging and the society that the majority of the family cars run by the sunlight and without supplying gas. Thus, we are developing high-efficiency and low-cost solar cells and modules for automobile applications. In this paper, our analytical results for the efficiency potential of various solar cells for choosing candidates of high-efficiency solar cell modules for automobile applications. This paper also presents our recent approaches: demonstration car (Toyota Prius PHV) by using Sharp's high-efficiency III-V triple-junction solar cell modules with an output power of 860 W, static low concentrator InGaP/GaAs/InGaAs triple-junction solar cell module with efficiency of 32.84%, and so forth.

KEYWORDS

high-efficiency solar cells, low-cost technologies, static concentration, tandem solar cells, vehicle application

1 | INTRODUCTION

According to Shell's "Sky Scenario,"[1] the cumulative capacity of photovoltaic (PV) power systems in the world by 2050 is 22 terra watts direct current (TW-DC). However, the total cumulative capacity of PV power systems in the world is only 635 GW-DC in 2019.[2] These suggest the importance of further installation of PV power systems and the importance of further development of science and technology and deployment of PV. Notably, the development of PV-powered vehicle applications is desirable and very important for the creation of new clean energy infrastructure based on PV.[3–5]

This paper presents the importance of developing high-efficiency and low-cost solar cells and modules for PV-powered vehicles. This paper also shows analytical results for the efficiency potential of various solar cells for choosing candidates of high-efficiency solar cell modules for vehicle applications. Our approaches to PV powered vehicle applications by using III-V triple-junction cell modules, static low concentrator III-V triple-junction solar cell modules and III-V/Si partial concentrator solar cell modules, and III-V/Si tandem cells are also shown.

2 | EFFICIENCY AND COST IMPACT ON PV-POWERED VEHICLES

Even in the automobile sector, reducing CO_2 emission is a critical challenge for contributing to sustainable development, because the proportion of the CO_2 emission from the road transport in the overall energy-related CO_2 emission in Japan, the United States, and the world are 16.3%, 30.5%, and 18.4%, respectively.[6] Figure 1 shows the CO_2 emission per 1 km driving for various types of vehicles in Japan[7] and the United States.[8] The following assumptions were used for the calculation; the CO_2 emission per 1 kWh electricity generation were 0.531 kg (Japan) and 0.580 kg (the United States), annual driving range was 10 000 km, and solar irradiation was 4.0 kWh/m^2/day that is average of the measured value in Nagoya, Japan. Although Battery-powered Electric Vehicle (BEV) has an advantage for less CO_2 emission compared with Internal Combustion Engine vehicle (ICE), Fuel Cell-powered vehicle (FCV), and Hybrid Electric Vehicle (HEV), further reduction in CO_2 emission is necessary. Therefore, PV can make a significant improvement in CO_2 emission, as shown in Figure 1. According to survey reports[9,10] of 5000 drivers and vehicles, a PV-powered EV (PV-EV) with 1 kW rated-power-PV, and a 4 kWh rated battery capacity would reduce 12% of CO_2 emission compared with the HEV for 12 years.

Figure 2 shows efficiency and cost impacts on PV-powered vehicle applications estimated from the survey reports.[9,10] This figure implies that R&D on PV is essential to introduce PV-powered vehicles as a clean and usable primary vehicle for the market. Notably, the development of high-efficiency and low-cost solar cells and modules is essential for PV-powered vehicles, as shown in Figure 2.

According to the NEDO's Interim Report "PV-Powered Vehicle Strategy Committee,"[3] a new broader PV market with more than 10 GW and 50 GW in 2030 and 2040, respectively, are expected to be established when PV-powered vehicles are developed. Cumulative PV capacity for PV-powered vehicles will be 50 GW and 0.4 TW in 2030 and 2040, respectively. The capacity was estimated as follows: The reported total sales of passenger cars in the world was around 75 million. When the 70% of the annual sold passenger cars are equipped with the 1 kW rated-power PV module, the potential of the annual market size is calculated to be 50 GW/year.

3 | NECESSITY AND SELECTION OF HIGH-EFFICIENCY SOLAR CELLS FOR PV-POWERED VEHICLES

3.1 | Necessity of high-efficiency solar cells for PV-powered vehicles

A report by the Ministry of Japan[11,12] 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. Standard EVs have an electricity consumption rate of approximately 9 km/kWh, but after the weight reduction of passenger cars from 1400 to 600 kg, the rate is expected to increase to 17 km/kWh.[13] Divided the range of 30 km by 17 km/kWh, the necessary electricity for passenger cars that do not require fossil fuel for driving is 1.76 kWh/day. Namely, the average annual energy yield that is required for the lightweight passenger car powered by sunlight will be 642 kWh/year which is not an incredible value but a promising one that generated on the car exterior, when we use a high-efficiency PV with an efficiency of higher than 30%, enables the society that majority of the Japanese passenger cars run by the solar power and without supplying fossil

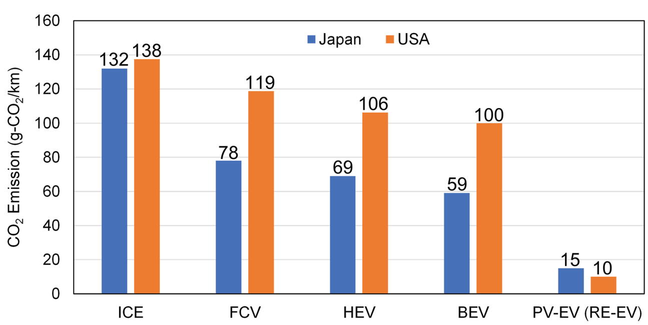


FIGURE 1 CO_2 emission per 1 km driving for various vehicles in Japan and the United States. The calculations were conducted based on the data described in previous studies[7,8] [Colour figure can be viewed at wileyonlinelibrary.com]

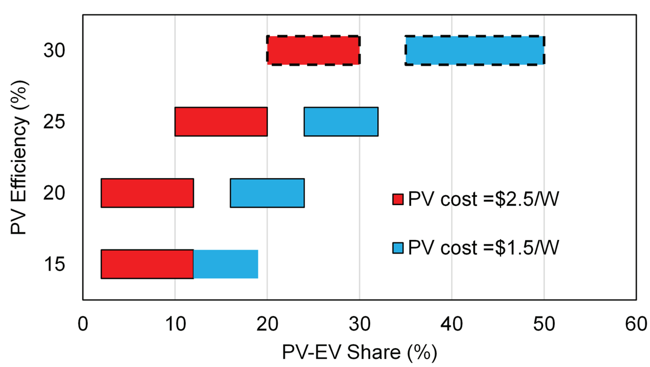


FIGURE 2 Sensitivity of photovoltaic (PV)-powered vehicle share on PV efficiency and cost estimated which were based on the data described in Kimura et al. and Hara et al.[9,10] [Colour figure can be viewed at wileyonlinelibrary.com]

fuels. Thus, we need to develop high-efficiency (over 30%), which cannot be achieved by single junction Si solar cells and low-cost solar cells/modules, for automotive applications.

Figure 3 shows the required conversion efficiency of solar modules as a function of its surface area and electric mileage to attain 30 km/day driving for passenger cars under the condition of solar irradiation of 3.7 $kWh/m^2/day$ (measured average value in Japan).[13] In the calculations, the charging system efficiency of 73.9% composing of cell temperature correction, maximum power point tracking, DC/DC conversion, and DC charging was assumed.[13] The figure shows that a promising way to realize the installation of PV on a passenger car is to create high-efficiency modules with efficiencies of 37% and 27% which can be installed on the roof area, roof, and engine food area whose surface areas is around 1.7 and 2.5 m^2, respectively in the case of electric mileage of 17 km/kWh. The PV module can be realized by using a III-V compound based multijunction (MJ) solar cells which have conversion efficiency larger than 37.9%[14] and 39.2%[15] under one sun illumination.

Figure 4 shows the calculated driving distance of PV-powered vehicles in the case of electric mileage of 17 km/kWh as a function of module efficiency and solar irradiation. PV-powered vehicles installed with a 30% efficiency module can drive with 45 km/day on average and at 90 km/day on a sunny day. It can be said that the 30% efficient PV module is a promising target for the PV-powered passenger car application. Note that the solar irradiation varies depend on location, but the value used in the calculations is close to the average value in the world. The longer driving range by the solar power can be expected in the region where the irradiation is higher than the average value. For example, the driving range is calculated to be longer than 60 km/day on average day in some regions in Europe and the United States.

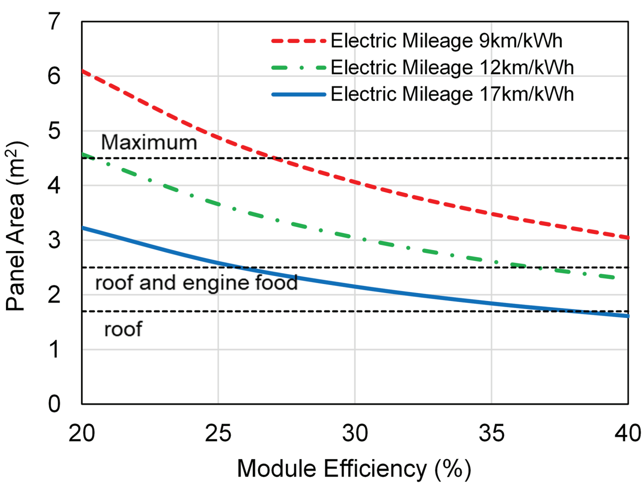


FIGURE 3 Required conversion efficiency of solar modules as a function of its surface area and electric mileage to attain 30 km/day driving. A preferable part of the installation is the vehicle roof. Note that this trend does not include the illumination environment condition of the roof, such as shading, incident angle distribution, spectrum change, and temperature [Colour figure can be viewed at wileyonlinelibrary.com]

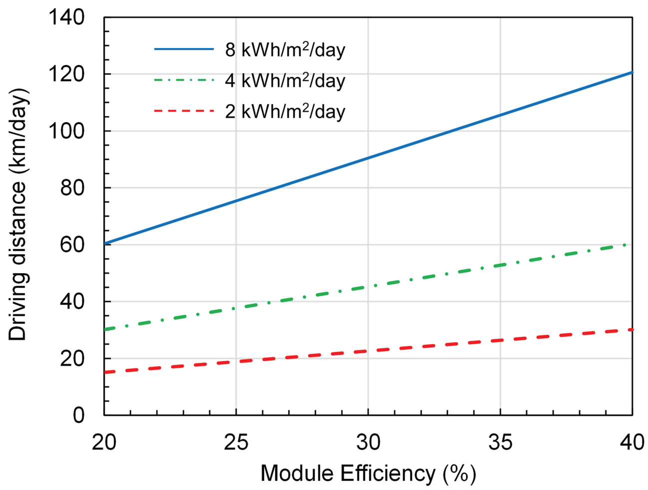


FIGURE 4 Calculated driving distance of photovoltaic (PV)-powered vehicles in the case of electric mileage of 17 km/kWh as a function of module efficiency and solar irradiation[13] [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | Selection of high-efficiency solar cell modules for PV-powered vehicles

Figure 5 shows the current status for efficiencies of various types of solar cells and modules as a function of cell and module areas.[16,17] As shown in Figure 5, only III-V compound MJ solar cells such as triple-junction solar cells are thought to be one of the candidates as 30% efficiency solar cells. Because current III-V compound-based cells have still higher cost, further developments of solar cell modules are necessary to realize the PV-powered passenger cars. Especially, usage of MJ (tandem) structure with different material systems, improvements in material and cell quality, and reduction in resistance loss are critical to developing higher efficient solar cell modules.

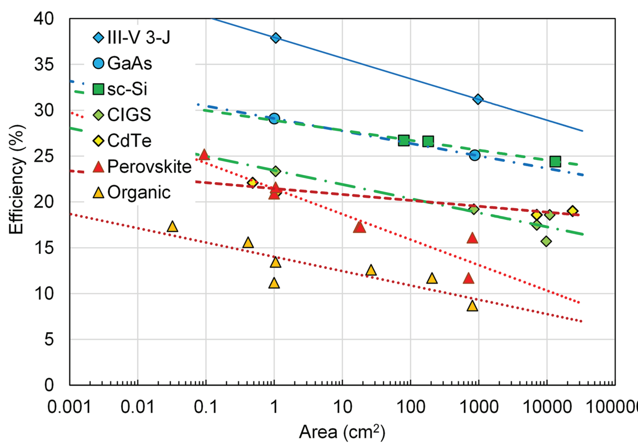


FIGURE 5 Current status for efficiencies of various types of solar cells and modules as a function of cell and module areas. The data described in Green et al.[16,17] were plotted in the figure. "3-J" means the triple-junction [Colour figure can be viewed at wileyonline library.com]

We developed a model for the analysis[18–20] for comparing the sources of efficiency loss of different types of solar cells. This model only attributes the efficiency loss to resistance loss and nonradiative recombination loss, which is a reasonable assumption because most solar cells have a minimal optical loss. The external radiative efficiency (ERE), which is the ratio of radiatively recombined carriers against all recombined carriers, is used for the quantification of the non-radiative recombination loss. In other words, we have ERE-1 at Shockley-Queisser limit.[21] Although the EREs of state-of-the-art solar cells have been reported in the publications such as references,[16,17,22–24] we estimated the following equation[25] estimated the EREs of various solar cells:

$$V_{oc} = V_{oc:rad} + (kT/q)\ln(\mathrm{ERE}), \tag{1}$$

where V_{oc} is the measured open-circuit voltage, $V_{oc:rad}$ is the radiative open-circuit voltage (V), k is Boltzmann constant (J/K), T is the temperature (K), and q is the elementary charge (C). We use the reported $V_{oc:rad}$ values extracted from Green and Yao et al.[26,27] in the analysis. The second term on the right-hand side of Equation 1 is denoted as $V_{oc:nrad}$ because it associates with the voltage-loss due to nonradiative recombination. In the case of MJ tandem solar cells, we define average ERE (ERE_{ave}) by using average Voc loss:

$$\Sigma(V_{oc,n} - V_{oc,rad,n})/n = (kT/q)\ln(ERE_{ave}). \tag{2}$$

The measured fill factor (FF) was used for the estimation of resistance loss of a solar cell. The ideal fill factor FF_0, defined as the fill factor without any resistance loss, is calculated by[28]

$$FF_0 = (v_{oc} - \ln(v_{oc} + 0.71))/(v_{oc} + 1), \tag{3}$$

where v_{oc} is

$$v_{oc} = V_{oc}/(nkT/q). \tag{4}$$

The measured FFs can then be related to shunt resistance and the series resistance by the following equation[28]:

$$FF \approx FF_0(1 - r_s)(1 - r_{sh}{}^{-1}) \approx FF_0(1 - r_s - r_{sh}{}^{-1}) = FF_0(1 - r), \tag{5}$$

where r_s is the series resistance and r_{sh} is the shunt resistance normalized to R_{CH}. The characteristic resistance R_{CH} is defined by[28]

$$R_{CH} = V_{oc}/J_{sc}, \tag{6}$$

r is the total normalized resistance defined by $r = r_s + r_{sh}{}^{-1}$.

In the case of MJ tandem solar cells, we define average FF_0 in Equation 3 by using average V_{oc}.

In the calculation, the highest values reported in Green et al.[16] were used as J_{sc}.

We estimated the potential conversion efficiency of various solar cells at different EREs. Figure 6 shows the calculated and obtained one-sun efficiencies of various candidate solar cells. Crystalline Si solar cells have a potential efficiency of 28.8% with total normalized resistance r of 0.02 by improvements in ERE from approximately 1% to 30%. GaAs cells have a potential efficiency of 30.0% with r of 0.02 by improvements in ERE from 22.5% to 40%. CdTe, CIGSe, and perovskite solar cells have potential efficiencies of 27.7% by improving ERE and reducing resistance loss. III-V-based triple-junction and six-junction cells have potential efficiencies of 42% and 46% with r of 0.02 by improvements in ERE from 3% to 30% and from 1% to 30%, respectively.

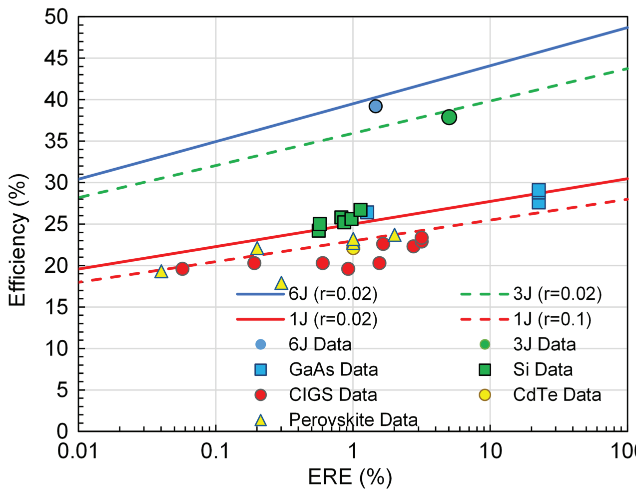
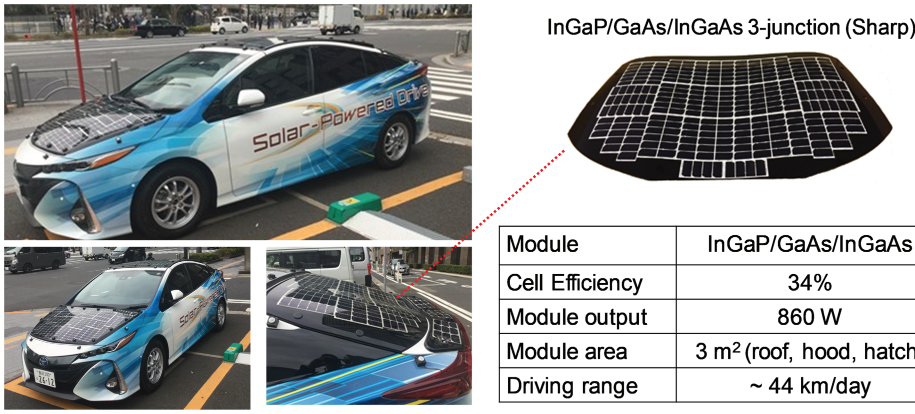


FIGURE 6 Calculated and obtained one-sun efficiencies of various solar cells based on the reported J_{sc} values[16,17]. "1J", "3J", and "6J" mean the single-junction, triple-junction, and six-junction, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

Table 1 shows a summary of potential and attained efficiencies of various candidate solar cells for PV-powered EV applications. Because of the space limitation of the car roof, it should be a high-efficiency solar module higher than 30%, as shown in Figure 6, III-V compound-based MJ cells and III-V/Si tandem cells are a candidate. Although the

TABLE 1 Summary of potential and achieved efficiencies of various candidate solar cells. "3J" and "6J" mean the triple-junction and six-junction, respectively

	Potential (%)	Attained (%)	Reach (%)	Year
Mono crystalline Si	28.8	26.7	92.7	2017
Gallium arsenide	30.0	29.1	97.0	2018
III-V based 3J	42.0	37.9	90.2	2013
III-V based 6J	46.0	39.2	85.2	2019
III-V/Si	42.0	35.9	85.5	2017
SLVPV (2–4 suns III-V/Si etc.)	40.0	27.6	69.0	2019
CIGS	27.7	23.4	84.5	2018
CdTe	27.7	22.1	79.8	2015
Perovskite	27.7	24.2	87.4	2019
Organic	20.2	16.4	81.2	2019



Module	InGaP/GaAs/InGaAs
Cell Efficiency	34%
Module output	860 W
Module area	3 m² (roof, hood, hatch)
Driving range	~ 44 km/day

FIGURE 7 Toyota Prius PHV demonstration car using InGaP/GaAs/InGaAs triple-junction (3-junction) solar cell module and characteristics[29] [Colour figure can be viewed at wileyonlinelibrary.com]

concentrator PV (CPV) is very attractive for saving the cost, trackers were considered to challenge to implement on a car roof because cars move quickly. Therefore, a static concentrator (SC) customized to the automotive application combined with III-V-based cell is promising.

4 | OUR RECENT APPROACHES FOR PV-POWERED VEHICLES

4.1 | Demonstration car by using III-V triple-junction cell modules

Most recently, Toyota has developed test car by using Sharp's high-efficiency InGaP/GaAs/InGaAs triple-junction solar cell modules (output power of 860 W, average cell efficiency of 34.9%) under the NEDO support[29] as shown in Figure 7. The maximum daily driving range of 44.5 km is expected to be realized by using solar energy. The measured radiation data in Nagoya from 1999 to 2009 was used for the estimation of the driving range. Data collection and analysis are under driving test by using the Toyota Prius PHV (plug-in hybrid vehicle) test car.

Figure 8 shows calculated results for changes in driving distance of PV-powered vehicles as a function of module efficiency and solar irradiation in comparison with practical data[30,31] for demonstration car powered by III-V MJ cell modules with 860 W and Toyota's Prius PHV (shipped in 2017)[30] powered Si HIT (heterojunction) cell modules of 180 W. In the calculation, 17 km/kWh and 10.54 km/kW[30] were used as electric mileage of demonstration car and Toyota's Prius PHV, respectively. As shown in Figure 8, vehicles powered by the higher efficiency solar cell modules have the longer driving distance potential. Differences between estimation and measured data suggest the effects of difference in direction of PV module face and partial shading.[31] The measured driving range of the demonstration car was 29.1 km/day at 4.1 kWh/day irradiation and 36.6 km/day at 6.2 kWh/day irradiation conditions, respectively.

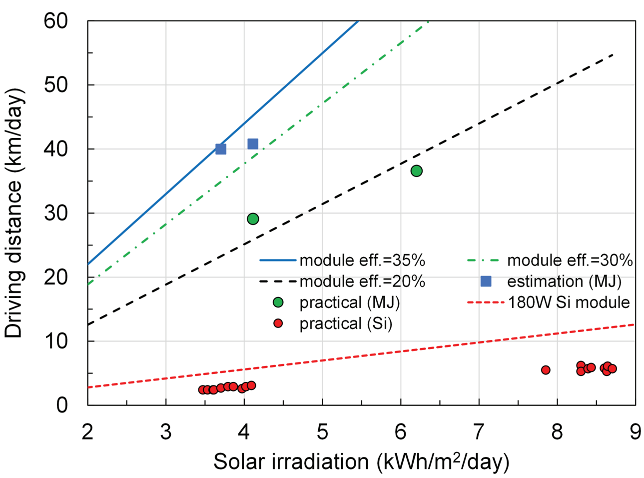


FIGURE 8 Calculated results for changes in driving distance of photovoltaic (PV)-powered vehicles as a function of module efficiency and solar irradiation in comparison with useful data for demonstration car with III-V multijunction (MJ) cell modules with 860 W and Toyota's Prius PHV with Si HIT cell modules with 180 W [Colour figure can be viewed at wileyonlinelibrary.com]

4.2 | Cost reduction approaches

Cost reduction of high-efficiency solar cell modules is also significant for PV-powered vehicle applications, as shown in Figure 2. Figure 2 implies that R&D on high-efficiency and low-cost PV is essential to introduce PV-powered vehicles as a clean and usable primary vehicle for the market. Although the III-V MJ solar cells[32] have an extremely high conversion efficiency with efficiencies of 39.2% without concentration systems,[15] which is suitable for PV-powered vehicle applications, cost reduction is necessary to realize this concept. Figure 9 shows module efficiency and module cost for III-V MJ solar cell modules, conventional flat Si PV solar cell modules, PV modules developed for Toyota Prius released in 2009, and those for Toyota New Prius released in 2017, and module efficiency and module cost targets of PV-EV.[33,34] Because module price estimated[33] are about \$30/W for Toyota Prius shipped in 2009 and \$12/W for New Prius shipped in 2017, respectively, it is thought that target of module cost may be less than \$10/W. Although the conventional flat Si PV is a low-cost, further improvement in module efficiency of more than 30% is necessary for PV-powered vehicle applications.

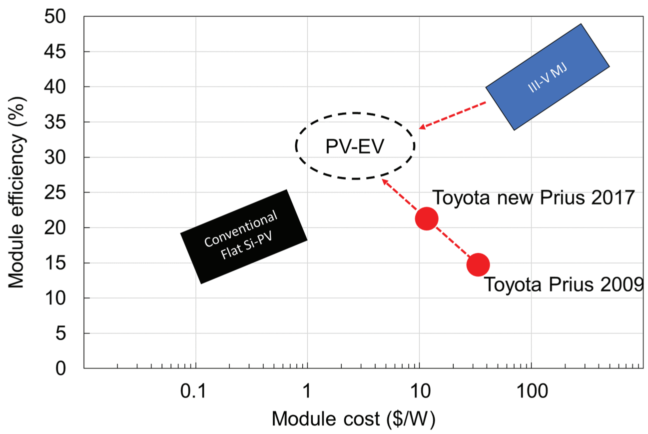


FIGURE 9 Module efficiency and module cost for III-V multijunction (MJ) solar cell modules, conventional flat Si photovoltaic (PV) solar cell modules, PV modules developed for Toyota Prius shipped in 2009, and those for Toyota New Prius shipped in 2017, and module efficiency and module cost targets of PV-EV [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 10 shows a comparison of module cost as a function of module production volume for III-V tandem, rapid deposition, Si tandem, and concentrator, reported by the authors[35] and cost analytical results for rapid deposition (hydride vapor phase epitaxy [H-VPE])[36] and Si tandem[37] by reported NREL. Therefore, ways for module cost reduction are reduction in film thickness, a high growth rate of films, reuse of substrates, Si tandem solar cells, and an increase in module production volume due to an increase in market size as shown in Figure 10. The results suggest that there are many possible ways to achieve $10/W for III-V-based solar cell module, such as scaling up production volume to 10 MW/year with a high-speed growth method, or using Si substrate instead of expensive GaAs or Ge substrate. In addition, concentrator is effective to reduce the cost of the solar cell module. We will describe each way in the following sections.

4.2.1 | High-speed deposition technology

H-VPE[38,39] has the potential to reduce deposition costs for III-V materials without sacrificing performance significantly. H-VPE uses elemental group III's, eliminating the processing needed to form metalorganics and enabling up to 10 times reduction in group-III input cost. H-VPE also provides higher throughput, with demonstrated GaAs growth rates up to 300 μm/h as well as improved reactant utilization. However, the complexity of H-VPE devices is limited by the difficulty of making abrupt and defect-free hetero-interfaces because the in situ generations of group-III metal chlorides means that alloy composition cannot be changed abruptly as in MOVPE (metalorganic vapor phase epitaxy).

Today, the H-VPE is much expected to reduce deposition cost for large area PV devices, as shown in Figure 10. That means there is a place for H-VPE as a route to less expensive III-V growth if more complex structures are enabling significantly high conversion efficiencies than Si can be developed. Recently, high-efficiency H-VPE grown GaAs solar cells with efficiencies of 25.31%[40] and 22.1%[39] by NREL and AIST, respectively, have been demonstrated. However, the current efficiency status of H-VPE grown InGaP/GaAs two-junction solar cells is 23.7%[38] by NREL and 21.8%[39] by AIST.

We have analyzed H-VPE grown InGaP/GaAs two-junction solar cells by using our analytical procedure described above. Figure 11 shows calculated and obtained one-sun efficiencies of H-VPE grown InGaP/GaAs two-junction solar cells in comparison with one-sun efficiency of conventional InGaP/GaAs two-junction solar cell.[17] Efficiencies and ERE values of H-VPE grown InGaP/GaAs two-

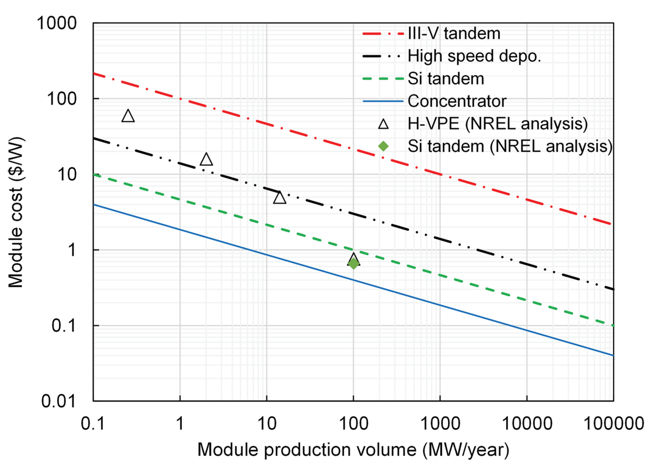


FIGURE 10 Comparison of module cost as a function of module production volume for a III-V tandem, Si tandem, and concentrator solar cell modules reported by Yamaguchi et al.[35] in comparison with cost analytical results for rapid deposition and Si tandem reported by NREL[36,37] [Colour figure can be viewed at wileyonlinelibrary.com]

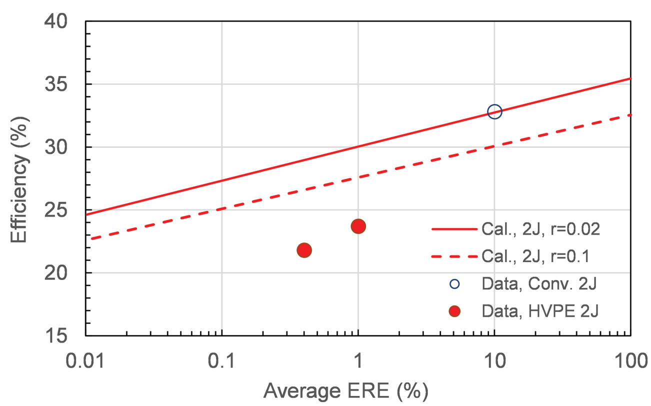


FIGURE 11 Calculated and obtained one-sun efficiencies of H-VPE grown InGaP/GaAs two-junction(2J) solar cells in comparison with one-sun efficiency of conventional InGaP/GaAs 2J solar cell. The data described in previous studies[38–40] were plotted in the figure. White circle presents 32.8% efficiency[17] by InGaP/GaAs 2J solar cell grown by Metal Organic Chemical Vapour Deposition (MOCVD) [Colour figure can be viewed at wileyonlinelibrary.com]

junction solar cells are still lower those of conversational MOVPE-grown InGaP/GaAs two-junction solar cells, as shown in Figure 11. Mainly, ERE (0.044%) of H-VPE grown InGaP subcells is quite lower than that (8.71%) of MOVPE-grown InGaP solar cells.[41] Therefore, further studies for improvements in ERE, resistance loss, and J_{sc} based on an understanding of bulk and interface recombination, and defects is necessary.

4.2.2 | Si tandem solar cells

The Si-based tandem cells that combine Si with other materials such as III-V compound, II-VI compound, and perovskite chalcopyrite are desirable for realizing super high-efficiency and low-cost, as shown in Figure 10. As a result, Si tandem solar cells[37,42] have been receiving considerable attention because of its potentials.

We have also analyzed the efficiency potential of various Si tandem solar cells.[42] In the analysis, the similar method and parameters described above were used. Figure 12 shows calculated one-sun efficiencies of III-V/Si triple-junction and two-junction tandem solar cells, perovskite/Si two-junction solar cells, CdZnTe/Si two-junction solar cell and GaAs nano-wire/Si two-junction solar cell in comparisons with efficiencies obtained as a function of average ERE and r_s + 1/r_{sh}. The triple-junction and two-junction Si tandem solar cells have an efficiency potential of 42% and 36%, respectively.

Previously, we achieved 28.2% efficiency (0.95-cm^2 da)[43,44] in 2016, and Sharp demonstrated 33%[45] (3.604-cm^2 ap) in 2017, with mechanically stacked InGaP/GaAs/Si triple-junction solar cells. At present, the III-V/Si triple-junction and two-junction tandem solar cells have shown higher efficiency with 35.9%[37] (1.002-cm^2 da) and 32.8%[37] (1.003-cm^2 da) compared with perovskite/Si two-junction tandem solar cells with efficiencies of 28.0% (1.030-cm^2 da)[17], CdZnTe/Si two-junction tandem solar cell with an efficiency of 16.8% (0.126-cm^2 mesa area)[46] and GaAs nano-wire/Si two-junction tandem solar cell with an efficiency of 11.4% (0.01-cm^2 ta).[47] It is noted that "da," "ap," and "ta" following the cell area represent designated area, aperture area, and total area, respectively. Such an efficiency difference is thought to be a difference in material quality. For example, the ERE values are 2%–4% for III-V/Si tandem cells, 1% and 2% for perovskite/Si tandem cells, 3.5 × 10^{-2}% for CdZnTe/Si tandem cells and 1 × 10^{-3}% for GaAs nano-wire/Si tandem cells. Therefore, a material quality is critical for further improvements in the performance of Si tandem solar cells. Although efficiency (35.9%)[37] of four-terminal mechanical stacked InGaP/GaAs/Si triple-junction tandem solar cells is close to that of InGaP/GaAs/InGaAs triple-junction cells (37.9% for 1.047-cm^2 ap),[14] resistance loss is higher as shown in Figure 12. Resistance loss for the perovskite/Si tandem cells, CdZnTe/Si tandem cells, and GaAs nano-wire/Si tandem cells are much higher compared with the III-V/Si tandem solar cells as shown in Figure 12.

The III-V/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 one-sun AM1.5 G, lightweight and low-cost potential.

The authors initiated the outdoor testing of Si tandem solar cells. Figure 13 shows our preliminary results[48] of output power measured and estimated for four-terminal InGaP/GaAs/Si tandem solar cell and InGaP/GaAs top cell and Si bottom cell. The four-terminal on Si tandem solar cell module has been demonstrated to have about 40% advantage in seasonal performance loss compared with standard InGaP/GaAs/InGaAs two-terminal tandem PV module.

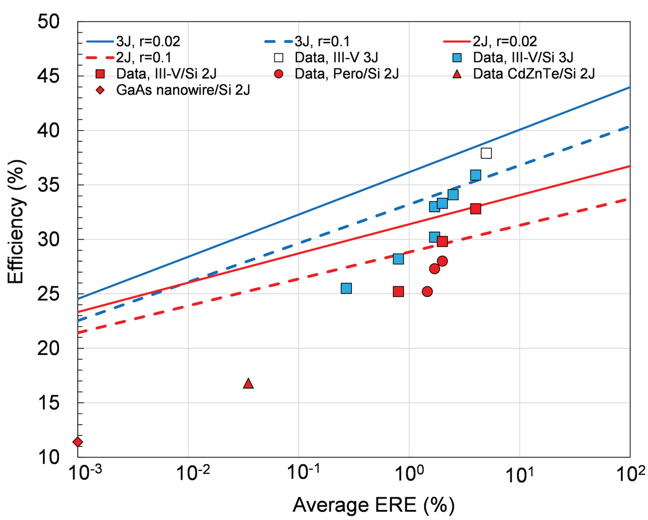


FIGURE 12 Calculated results of the efficiency of III-V/Si triple-junction (3J) and two-junction (2J) solar cells, perovskite/Si 2J solar cells, CdZnTe/Si 2J solar cell, and GaAs nano-wire/Si 2J cell under one-sun illumination condition in comparison with efficiencies obtained[17,37,43–47] as a function of ERE and r_s + 1/r_{ss}. White rectangular presents 37.9% efficiency by metamorphic InGaP/GaAs/InGaAs 3J solar cells[14] [Colour figure can be viewed at wileyonlinelibrary.com]

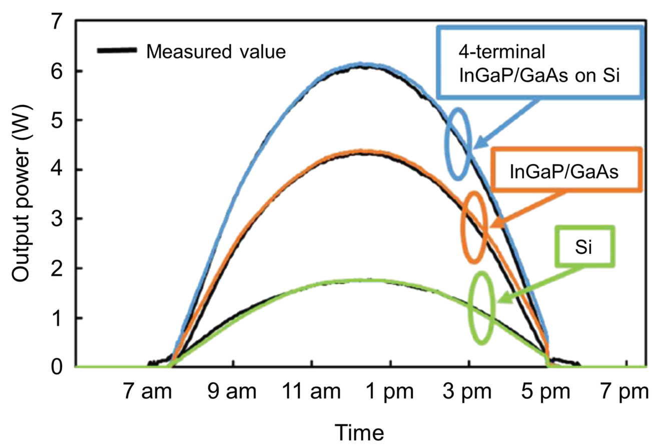


FIGURE 13 Output powers measured and estimated for four-terminal InGaP/GaAs/Si tandem solar cell, and InGaP/GaAs top cell and Si bottom cell[Colour figure can be viewed at wileyonline library.com]

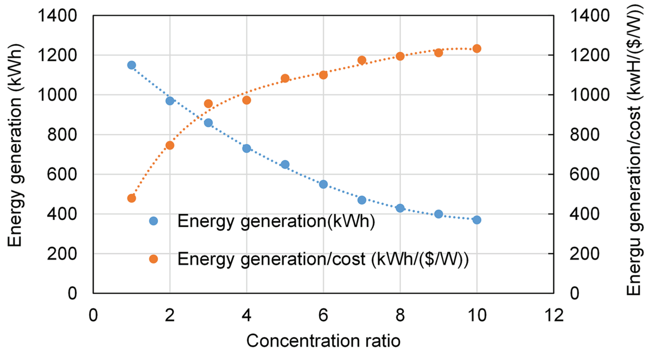


FIGURE 14 Calculated results for changes in annual energy generation and energy generation/cost from static low concentrator III-V/Si tandem solar cell modules as a function of concentration ratio. The calculations were conducted based on the analytical results reported in Araki et al. and Makita et al.[49,50] [Colour figure can be viewed at wileyonlinelibrary.com]

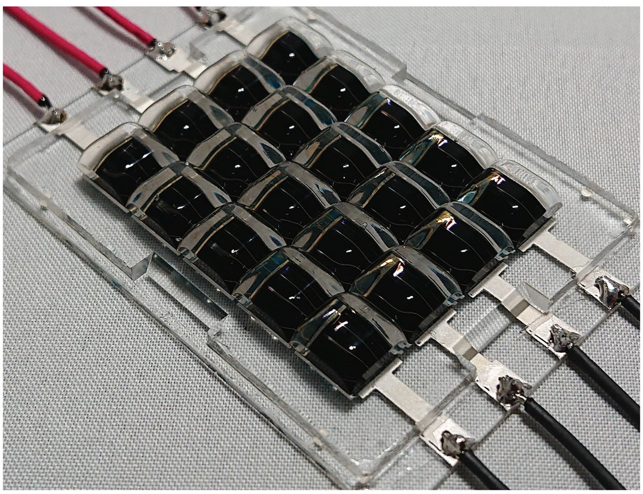


FIGURE 15 Photo of prototype static low concentrator module with III-V based triple-junction solar cell[51] [Colour figure can be viewed at wileyonlinelibrary.com]

4.2.3 | Static low concentrator technology

Also, utilizing a concentrator can lower the solar cell module cost by reducing the total cell area, as shown in Figure 10. Because it is hard to install a tracker on a vehicle roof, an SC is suitable for this application. SCs with III-V cells have many other advantages for automotive applications: (a) mounting on a three-dimensional curved surface is possible, (b) robustness to partial shading, and (c) possible aero-dynamics advantages using a shark-skin structure. The robustness to partial shading enables a high open-circuit voltage for the cells, allows a bypass diode to be equipped with each cell in the vacant space of the back-plate, and facilitates size reduction of the lens/cell pair aperture. As described above, Si solar cells are not thought to be sufficient even with a considerable (about 3 m^2) roof space, as shown in Figure 3. Figure 14 shows changes in annual energy generation and energy generation/cost from III-V/Si tandem solar cell modules as a function of concentration ratio. The calculation was made by combining our analytical results[49] of annual energy generation for static low concentrator III-V/Si tandem solar cell modules and cost analytical results for III-V tandem solar cell modules reported by AIST.[50] III-V/Si tandem solar cells and static low concentrator PV up to five-sun concentrations that satisfy the average annual of 642 kWh/year to be needed to the lightweight family car powered by sunlight are thought to be a candidate for vehicle installations.

New static low concentrators were proposed[4,13] for the vehicle applications. Most recently, we have achieved 32.84% efficiency[51] with static low concentrator InGaP/GaAs/InGaAs triple-junction solar cell module (area of 10.76 cm^2), as shown in Figure 15.

5 | SUMMARY

The authors have shown that solar modules for PV-powered vehicles have a great ability to reduce CO_2 emission. Impacts on efficiency and cost for PV-powered vehicles were also presented. According to the NEDO's Interim Report "PV-Powered Vehicle Strategy Committee," a new broader PV market with a cumulative PV capacity of more than 50 GW and 0.4 TW in 2030 and 2040, respectively, are expected to be established when PV-powered vehicles are developed. The development of high efficiency (>30%), low-cost, colored, and flexible modules are essential. Cost reduction approaches such as rapid deposition of III-V compound materials and solar cells, Si tandem solar cells, and SC PV were overviewed, and their efficiency potentials were discussed. SC PV, Si tandem PV, and colored PV are attractive candidates for future car applications. This paper also presents our recent approaches: Demonstration car using Sharp's high-efficiency III-V triple-junction solar cell modules, static low concentrator InGaP/GaAs/InGaAs triple-junction solar cell module with efficiency of 32.84%.

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