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Role of PV-Powered Vehicles in Low-Carbon Society and Some Approaches of High-Efficiency Solar Cell Modules for Cars

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Abstract

Development of highly-efficient photovoltaic (PV) modules and expanding its application fields are significant for the further development of PV technologies and realization of innovative green energy infrastructure based on PV. Especially, development of solar-powered vehicles as a new application is highly desired and very important for this end. This paper presents the impact of PV cell/module conversion efficiency on reduction in CO_2 emission and increase in driving range of the electric based vehicles. Our studies show that the utilization of a highly-efficient (higher than 30%) PV module enables the solar-powered vehicle to drive 30 km/day without charging in the case of light weight cars with electric mileage of 17 km/kWh under solar irradiation of 3.7 kWh/m^2/day, which means that the majority of the family cars in Japan can run only by the sunlight without supplying fossil fuels. Thus, it is essential to develop high-efficiency as well as low-cost solar cells and modules for automotive applications. The analytical results developed by the authors for conversion efficiency potential of various solar cells for choosing candidates of the PV modules for automotive applications are shown. Then we overview the conversion efficiency potential and recent progress of various Si tandem solar cells, such as III-V/Si, II-VI/Si, chalcopyrite/Si, and perovskite/Si tandem solar cells. The III-V/Si tandem solar cells are expected to have a high potential for various applications because of its high conversion efficiency of larger than 36% for dual-junction and 42% for triple-junction solar cells un-

der 1-sun AM1.5 G illumination, lightweight and low-cost potentials. The analysis shows that III-V based multi-junction and Si based tandem solar cells are considered to be promising candidates for the automotive application. Finally, we report recent results for our 28.2% efficiency and Sharp's 33% mechanically stacked InGaP/GaAs/Si triple-junction solar cell. In addition, new approaches which are suitable for automotive applications by using III-V triple-junction, and static low concentrator PV modules are also presented.

Keywords

Solar Cell Powered Vehicle Applications, High-Efficiency Solar Cells, Multi-Junction Solar Cells, Tandem Solar Cells, Modules

1. Introduction

The solar electricity including solar photovoltaics (PV) is expected to contribute to the primary energy with a share of approximately 20% and 70% in 2050 and 2100, respectively. It respectively occupies in the total energy of the world, according to the recommendation (World Energy Vision 2100) by the German Advisory Council on Global Change [1]. According to "Sky Scenario" reported by Shell [2], the cumulative capacity for the power systems based on PV in the world is reached to 22 TW by 2050. However, the number is only 600 GW in 2019. The fact suggests that the importance of further installation of the PV based power systems, and the importance of further development of science and technology and deployment of PV. Especially, development of PV-powered vehicles applications is desirable and very important for creation of new clean energy infrastructure based on PV [3] [4]. In order to realize PV-powered vehicles, development of high-efficiency, low-cost, light weight, 3-dimensional curved and colorful solar cell modules is necessary.

This paper especially presents the importance of developing highly-efficient and low-cost solar cells and modules for automotive applications by showing efficiency impact on PV-powered vehicles in Section 2 and cost impact on them in Section 4. This paper also shows analytical results for efficiency potential of various types of solar cells in order to provide knowledge for selecting candidates of high-efficiency solar cell modules for automotive applications as described in Section 3. In Section 5, 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 reported.

2. Efficiency Impact on PV-Powered Vehicles

Even in the transport sector, reducing CO_2 emission is a critical challenge for contributing to sustainable development, because the proportion of CO_2 emission from the road transport in the overall energy-related CO_2 emission in Ja-

pan, USA, and the world are 15.9%, 27.8%, and 16.9%, respectively [5]. **Figure 1** shows the CO_2 emission per 1 km driving for various types of vehicles in Japan [6]. Although BEV (Battery-powered Electric Vehicle) has advantage for less CO_2 emission compared to ICE (Internal Combustion Engine vehicle), FCV (Fuel Cell-powered vehicle), and HEV (Hybrid Electric Vehicle), it is essential to achieve further reduction in CO_2 emission. **Figure 1** shows that the PV can make a significant improvement on CO_2 emission.

According to survey reports [7] [8] of 5000 people and vehicles, effectiveness of the PV-EV (PV-powered EV), a PV-EV with 1 kW rated-power-PV and a 4 kWh rated battery capacity would reduce 12% of CO_2 emission compared to the HEV for 12 years.

In addition, the development of infra-structures such as battery charging stations for BEV and hydrogen stations for FCV is delayed. **Figure 2** shows changes in cumulative registration number of Nissan LEAF (BEV) and number of the installed quick chargers [9] [10]. Therefore, development of PV-powered vehicles
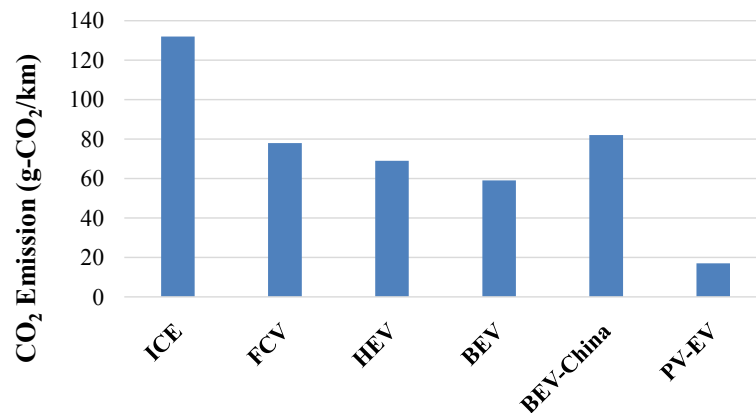

Figure 1. CO_2 emission per 1 km driving for various vehicles in Japan.
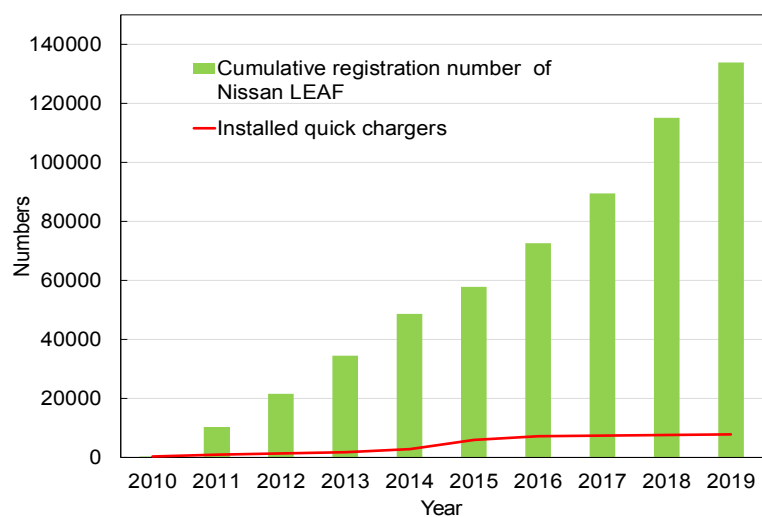

Figure 2. Changes in cumulative registration number of Nissan LEAF (BEV) and number of quick chargers installed.

is very useful to overcome the gap between registration number of BEV and charging stations.

Figure 3 shows the conversion efficiency of PV modules impact on PV-powered vehicle applications estimated from the survey reports [7] [8]. This figure implies that R&D on PV is essential in order to introduce PV-powered vehicles as a clean and usable major vehicle for the market. Especially, development of high-efficiency solar cells and modules is essential for PV-powered vehicles.

Figure 4 shows the prediction of projected cumulative number of PV-powered vehicles according to the NEDO's Interim Report by "PV-Powered Vehicle Strategy Committee" [3]. According to the NEDO's report, new broader PV market with more than 10 GW and 50 GW in 2030 and 2050, respectively are expected to be established. Cumulative PV capacity for PV-powered vehicles will be 50 GW and 0.4 TW in 2030 and 2050, respectively.
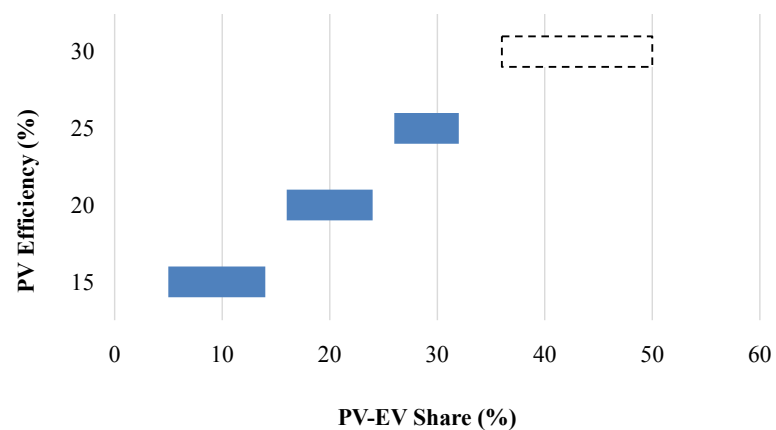

Figure 3. Sensitivity of PV-powered vehicle share on PV efficiency estimated.
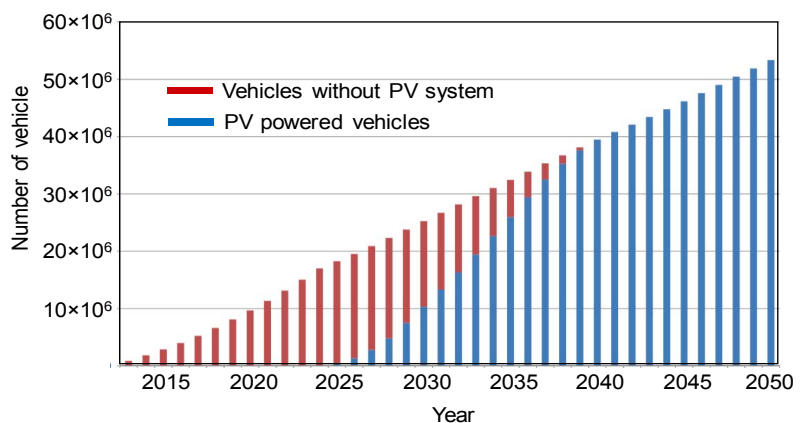

Figure 4. Prediction of several PV-powered vehicles according to the NEDO's Interim Report "PV-Powered Vehicle Strategy Committee".

3. Necessity and Selection of High-Efficiency Solar Cell Modules for PV-Powered Vehicles

According to a statistics by Ministry of Japan [11] [12], approximately 70% of

the family car runs less than 30 km per day in Japan. Standard EV runs approximately 9 km per kWh electricity, but after weight saving from 1400 kg 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 will be 1.76 kWh/day. Namely, the average annual energy yield that is required for the light-weight family car powered by sunlight will be 642 kWh/year which is not an impossible value as well as a promising when we use a high-efficiency PV with efficiency of larger than 30% enables the society that majority of the family cars run by the solar power and without supplying fossil fuels. Thus, it is important for us to develop high-efficiency and low-cost solar cells and modules for automotive applications.

Figure 5 shows the required module efficiency as a function of the solar cell module area for the solar cell modules to achieve 800 W rated-output power [13]. The figure suggests that a promising way to realize the installation of PV on a family car is to create a small size module with 800 W rated output power which can be installed on roof area. The PV module can be realized by using III-V compound multi-junction solar cells which have conversion efficiency larger than 33% under 1 sun illumination.

Therefore it can be said that the development of a highly-efficient PV module with an efficiency of larger 30% is important to realize PV-powered vehicles. Figure 6 shows the recorded conversion efficiency of various types of single-junction solar cells along with their extrapolations [14]. The data were fitted with the Goetzberger function [15]:

$$\eta(t) = \eta_{limit}\left[1 - \exp(t_0 - t)/c\right], \tag{1}$$

where $\eta(t)$ is the time-dependent efficiency, η_{limit} is the practical limiting efficiency, t_0 is the year for which $\eta(t)$ is zero, t is the calendar year, and c is a characteristic
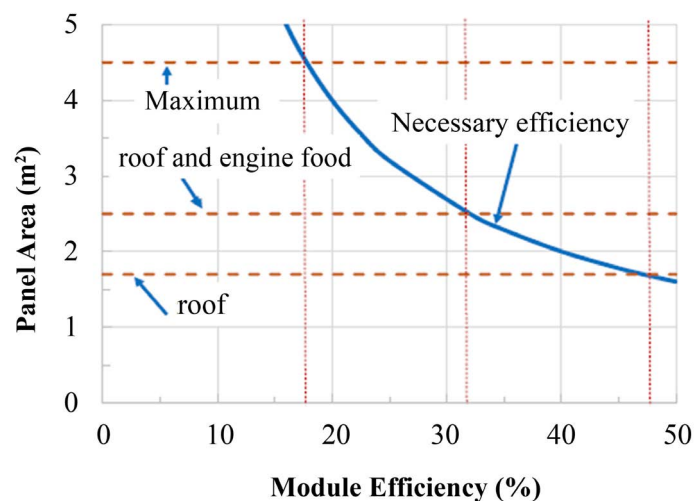

Figure 5. Required solar cell modules efficiency as a function of module area for an 800 W solar cell module installation on family cars. A preferable part of the installation is the vehicle roof. Note that this trend does not include the illumination environment condition of the roof, such as shading, incident angle distribution, spectrum change, and temperature.
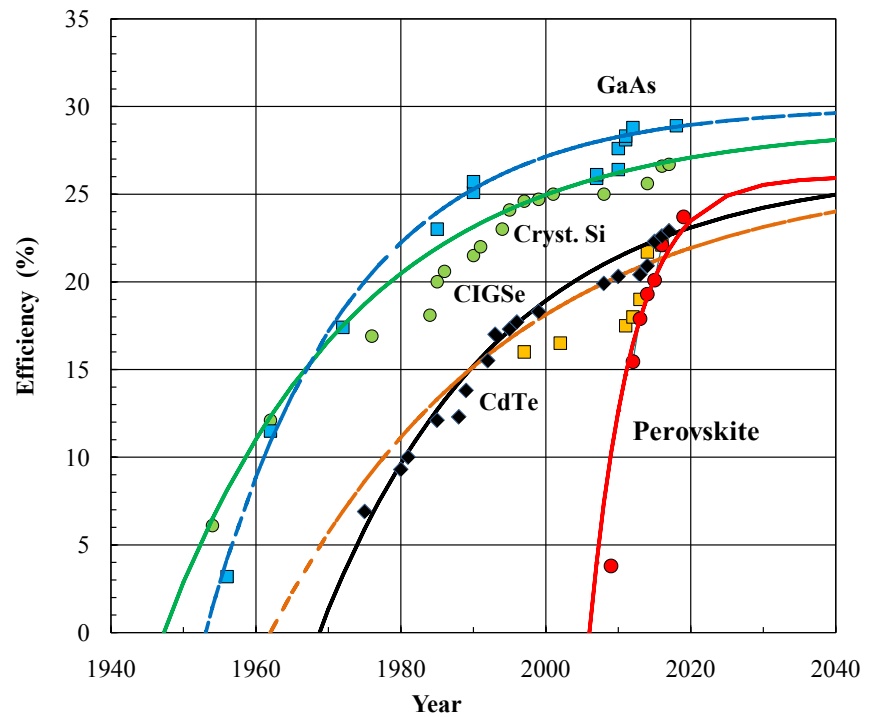
Figure 6. World record efficiencies of various solar cells over years. Solid and dashed lines are the fitted trajectories using Equation (1).

development time. Fitting of the curve was done with three parameters which are given in **Table 1**. The analysis shows that the improvement of the conversion efficiencies for each cell is converging or will converge soon, which is mainly bounded by the Shockley-Queisser limit [16].

Table 2 summarizes the reported world-record conversion efficiencies [14] [17] [18] [19] [20] [21] for various solar cells and Japanese contributions. As shown in **Table 2**, Japanese team has contributed to development of high-efficiency solar cells greatly as a result of Japanese national PV R&D programs such as the NEDO projects.

In this part, analytical results for efficiency potential of various solar cells are presented. We developed a model for the analysis [14] [17] for comparing the sources of efficiency loss of different types of solar cells. This model only attributes the efficiency loss to non-radiative recombination and resistance 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 [16]. The EREs of state-of-the-art solar cells have been reported in the publications such as references [18] [19] [20] [21]. In this work, the EREs of various solar cells were estimated by the following equation [22]:

$$V_{oc} = V_{oc:rad} + (kT/q)\ln(\text{ERE}), \tag{2}$$

where V_{oc} is the measured open-circuit voltage, k is Boltzmann constant, T is the

Table 1. Fitting parameters used in the fitting.

Solar cells	η_{limit}	c	t_0
GaAs	30	20	1953
Crystalline Si	29	27	1948
CdTe	26.5	33	1962
CIGSe	26.5	25	1968
Perovskite	26	6	2006

Table 2. Summary of world-record efficiencies for various solar cells and Japanese contributions.

Solar Cells	World Record Efficiency (%)	Japanese Contribution
Mono crystal Si	26.7	Kaneka
Concentrator Si	27.6	
Poly crystal Si	22.3	
a-Si	10.2	AIST
μc-Si	11.9	AIST
Thin-film Si triple-junction tandem	14.0	AIST
CuInGaSe$_2$	22.35	Solar Frontier
CdTe	22.1	
GaAs	29.1	
Concentrator GaAs	29.3	
III-V dual-junction	32.8	
Concentrator III-V dual-junction	35.5	
III-V tripole-junction	37.9	Sharp
Concentrator III-V triple-junction	44.4	Sharp
Concentrator III-V quad-junction	46.0	
III-V penta-junction	38.8	
III-V hexa-junction	39.2	
Concentrator III-V hexa-junction	47.1	
Perovskite	24.2	
Dye-sensitized	11.9	Sharp
Organic	11.2	Toshiba

absolute temperature, and q is the elementary charge. $V_{oc:rad}$ is the radiative open-circuit voltage. We use the reported $V_{oc,rad}$ values extracted from [23] [24] in the analysis. The offsets of $E_g/q - V_{oc,rad}$ used in the calculations are 0.23 V for CIGS, CdTe, a-Si and OPV, 0.25 V for perovskite, 0.26 V for Si, 0.28 V for III-V compounds [17] [24]. The second term on the right-hand side of Equation (2) is denoted as $V_{oc,nrad}$ because it associates to the voltage-loss due to non-radiative

recombination. In the case of multi-junction tandem solar cells, we define average ERE (ERE$_{ave}$) by using average *Voc* loss:

$$\Sigma\left(V_{oc,n} - V_{oc,rad,n}\right)/n = \left(kT/q\right)\ln\left(\mathrm{ERE}_{ave}\right), \tag{3}$$

where *n* is the number of junction.

The resistance loss of a solar cell is estimated solely from the measured fill factor. The ideal fill factor FF_0, defined as the fill factor without any resistance loss, is estimated by [25]

$$FF_0 = \left(v_{oc} - \ln\left(v_{oc} + 0.71\right)\right)/\left(v_{oc} + 1\right), \tag{4}$$

where v_{oc} is

$$v_{oc} = V_{oc}/\left(nkT/q\right). \tag{5}$$

The measured fill factors can then be related to the series resistance and shunt resistance by the following equation [25]:

$$FF \approx FF_0\left(1 - r_s\right)\left(1 - r_{sh}^{-1}\right) \approx FF_0\left(1 - r_s - r_{sh}^{-1}\right) = FF_0\left(1 - r\right), \tag{6}$$

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 [25]

$$R_{CH} = V_{oc}/J_{sc}, \tag{7}$$

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

In the calculation, highest values [21] obtained were used as J_{sc}.

By assuming no optical loss, we can project the efficiency of various solar cells at different EREs. **Figure 7** shows calculated and obtained one-sun efficiencies of
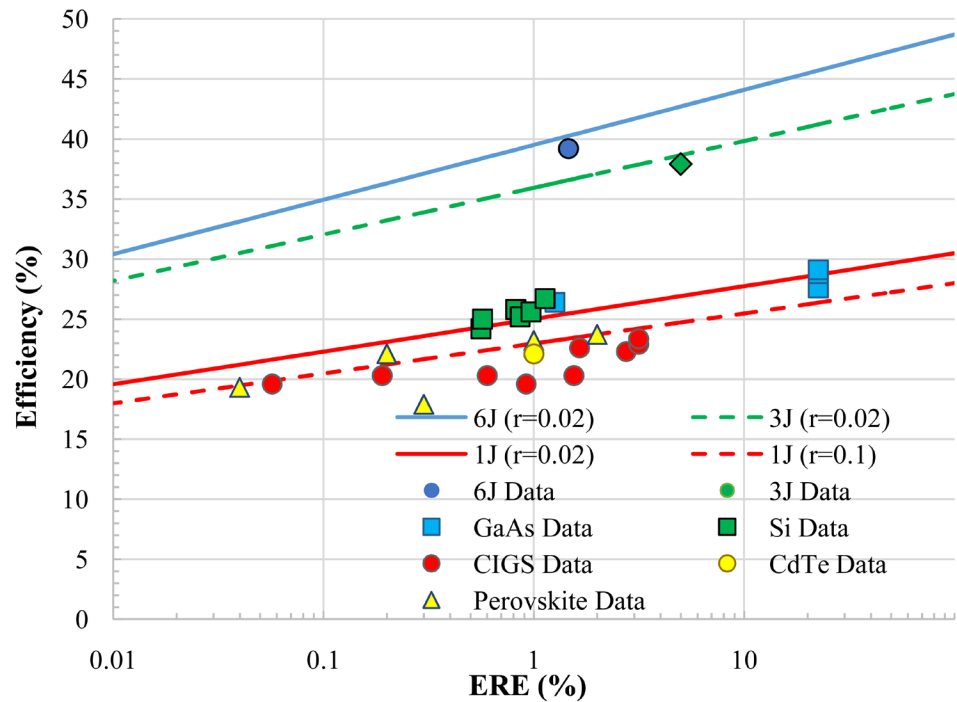

Figure 7. Calculated and obtained one-sun efficiencies of various solar cells.

various solar cells. In summary, crystalline Si solar cells have a potential efficiency of 28.8% with total normalized resistance r of 0.02 by improvements in ERE from around 1% to 30%. GaAs has a potential efficiency of 30.0% with r of 0.02 by improvements in ERE from 22.5% to 40%. III-V triple-junction and penta-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. CIGSe, CdTe and perovskite cells have potential efficiencies of 26.5% with r of 0.02 by improvements in ERE from around 1% to 10%.

Table 3 summarizes efficiency potential and efficiencies achieved of various candidate solar cells for PV-powered EV applications. The first request is a high-efficiency PV panel on the roof of the car. Because of the space limitation, it should be a high-efficiency panel. III-V compound multi-junction (tandem) cells and III-V/Si tandem cells are one candidate. The CPV (concentrator PV) is very attractive for saving the cost of the cell. Cars move quickly, and appearance is essential. Trackers were thought to challenge to implement. One of our choices is a static concentrator customized to the automobile.

Regarding III-V multi-junction solar cells, efficiency of multi-junction solar cells increases with increase in number of junction as shown in Figure 8. However, it is thought that triple-junction is optimal number of junction because in the case of higher number of multi-junction solar cells of more than quad-junctions, external radiative efficiency (ERE) decreases with increase in number of junction as shown in Figure 8. Fill factor for multi-junction solar cells is also decreases with increase in number of junction as shown in Figure 9.

In addition to high-efficiency and low-cost, development of PV modules with 3-dimesional curvature, color variation and good temperature coefficient is necessary. Figure 10 shows changes in temperature coefficients of various solar cells as a function of open-circuit voltage of solar cells [26] [27] in comparison of calculated values. Calculated values of relative temperature coefficients $TC_{rel.}$ of solar cells were semi-empirical equation [28].

Table 3. Summary of efficiency potential and efficiencies achieved of various candidate solar cells for PV-powered EV applications.

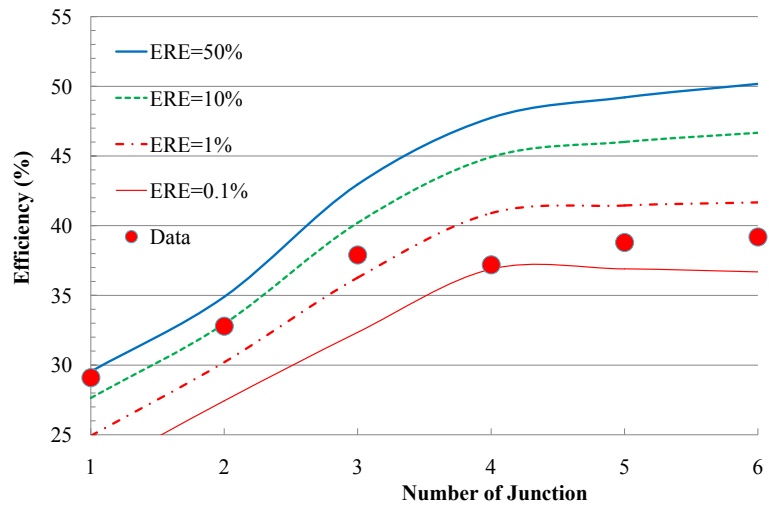| Solar Cells	Potential	Achieved	Reach
Mono crystalline Si	28.8%	26.7%	92.7%
Gallium arsenide	30.0%	29.1%	97.0%
III-V based triple-junction	42.0%	27.9%	90.2%
III-V based penta-junction	45.5%	38.8%	85.3%
III-V/Si	42.0%	35.9%	85.5%
SLCPV (2-4 suns III-V/Si etc.)	40.0%	27.6%	69.0%
CIGS	27.7%	23.4%	84.5%
CdTe	27.7%	22.1%	79.8%
Perovskite	27.7%	24.2%	87.4%
Organic	20.2%	16.4%	81.2%

Figure 8. Dependence of number of junction and external radiative efficiency (ERE) upon realized efficiencies and calculated efficiencies of multi-junction solar cells.
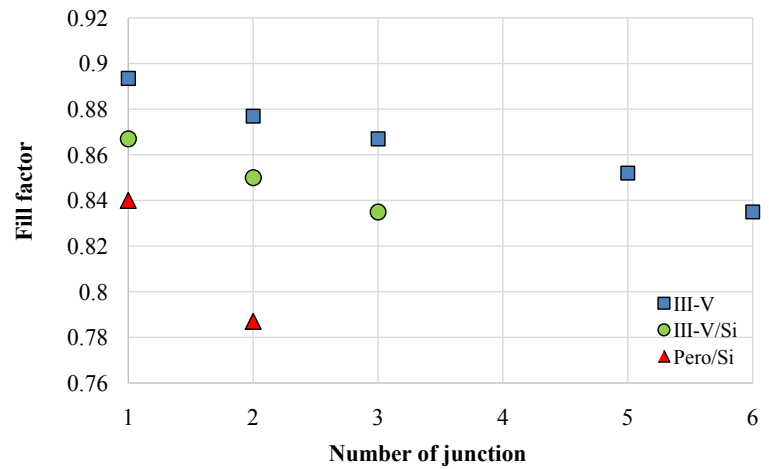

Figure 9. Dependence of number of junction upon realized fill factor of III-V, III-V/Si and perovskite/Si multi-junction tandem solar cells.
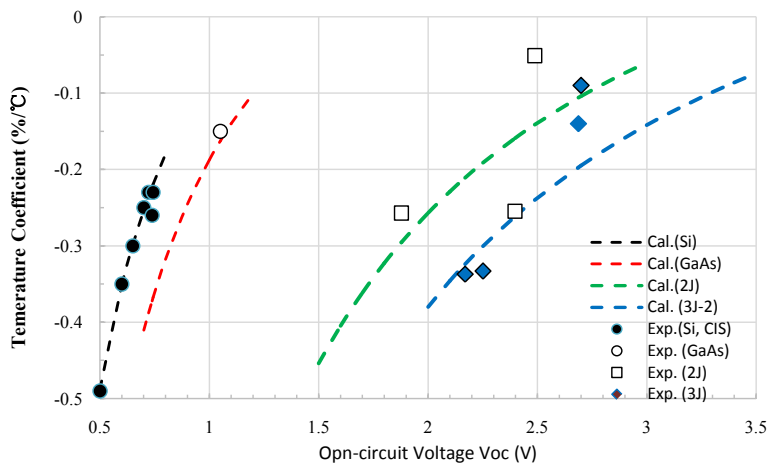

Figure 10. Changes in temperature coefficients of various solar cells as a function of open-circuit voltage of solar cells in comparison of calculated values (dotted lines).

$$TC_{rel.} = \left(1 - nE_g \big/ qV_{oc}\right)\Big/T = \left(1 - 1.1E_g \big/ qV_{oc}\right)\Big/T \,, \tag{8}$$

where n is the diode ideality factor. Because the III-V triple-junction solar cells have lower temperature coefficients of 0.09% - 0.15%/°C, compared to that (0.24%/°C) mono crystal Si solar cells as shown in Figure 10, the higher efficiency solar cells are thought to be attractive for PV-powered vehicle applications.

4. Cost Impact on PV-Powered Vehicles and Potential of High-Efficiency Low-Cost Si Tandem Solar Cells

Cost reduction of high-efficiency solar cell modules is also very important for PV-powered vehicle applications. Figure 11 shows cost impact on PV-powered vehicle applications estimated from the survey reports [7] [8]. This figure implies that R&D on high-efficiency and low-cost PV is essential in order to introduce PV-powered vehicles as a clean and usable major vehicle for the market.

Although III-V multi-junction solar cells have an extremely high conversion efficiency with efficiencies of 39.2% under 1-sun and 47.1% under concentration, which is suitable for this application, cost reduction is necessary to realize the concept as shown in Figure 5.

Figure 12 shows module efficiency and module cost for III-V multi-junction (MJ) solar cell modules, conventional flat Si PV solar cell modules, PV modules developed for Toyota PRIUS released in 2010 and those for Toyota New PRIUS released in 2017, and module efficiency and module cost targets of PV-EV [29] [30]. Because module price estimated [29] are about $30/W for Toyota Prius released in 2010 and $12/W for New Prius released in 2017, respectively, it is thought that target of module cost may be less than $10/W.

Figure 13 shows a comparison of module cost for III-V tandem (MJ), III-V/Si tandem (MJ), and concentrator III-V/Si tandem solar cell modules as a function of module production volume [31]. The III-V/Si tandem solar cell modules have low-cost potential if technology development, expansion of application areas and an increase in output volume is made.
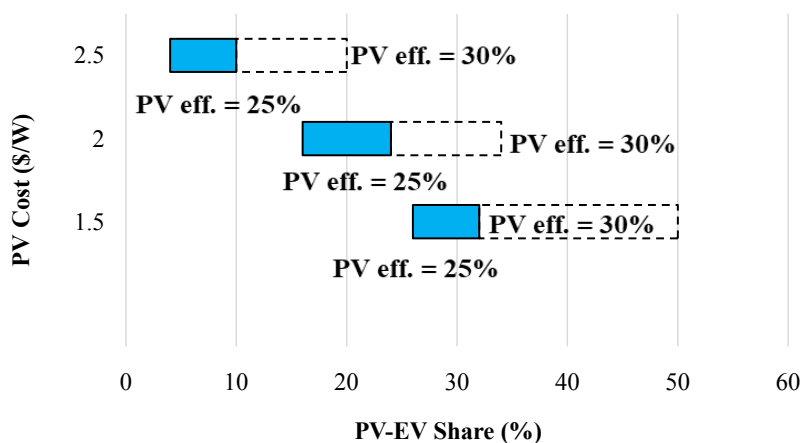

Figure 11. Cost impact on PV-powered vehicle applications estimated from the survey reports in case of PV efficiencies of 25% and 30%.
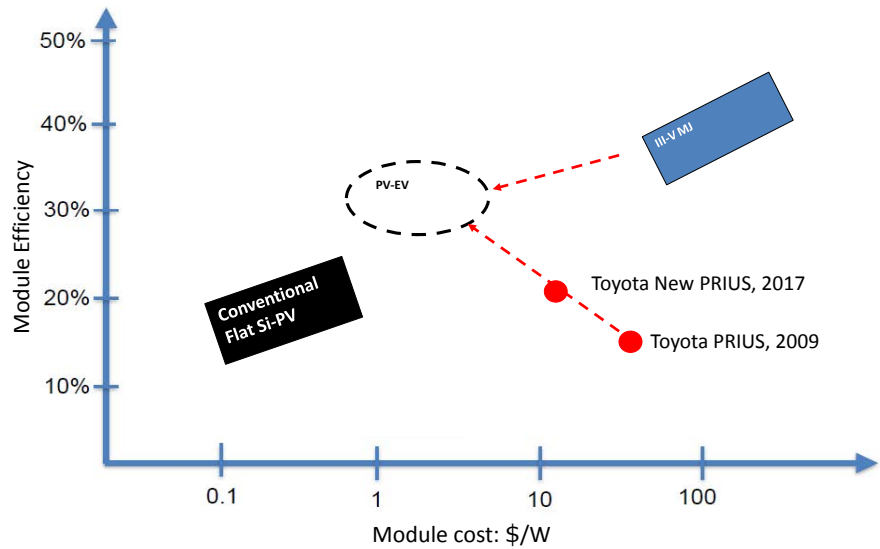
Figure 12. Module efficiency and module cost for III-V multi-junction solar cell modules, conventional flat Si PV solar cell modules, PV modules developed for Toyota PRIUS released in 2010 and those for Toyota New PRIUS released in 2017, and module efficiency and module cost targets of PV-EV.
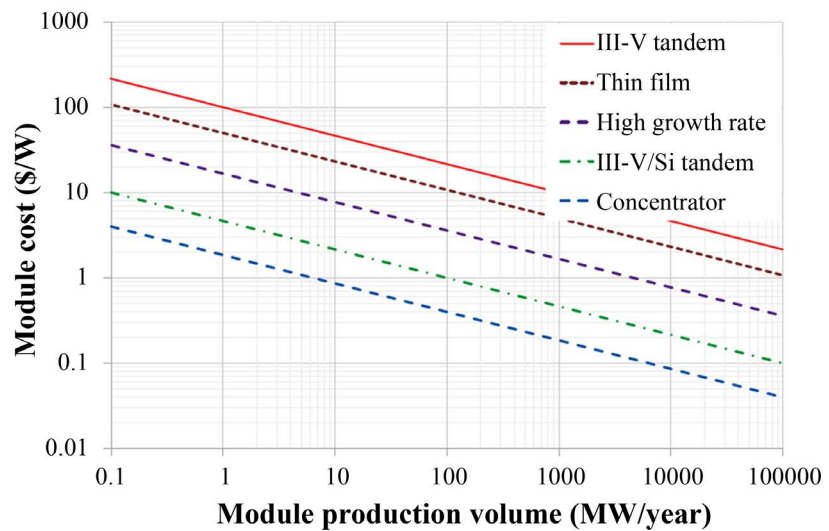

Figure 13. Comparison of module cost for an III-V tandem, III-V/Si tandem, and concentrator III-V/Si tandem solar cell modules as a function of module production volume.

Therefore, Si tandem solar cells by combining Si and other materials such as III-V compound, II-VI compound, chalcopyrite, perovskite and so forth are desirable for realizing super high-efficiency and low cost. Recently, Si tandem solar cells have paid considerable attention because of high-efficiency and low-cost potential.

Efficiency potential of various Si tandem solar cells is also analyzed [32]. The similar procedure and values described above were used. **Figure 14** shows calculated 1-sun efficiency of III-V/Si triple-junction and dual-junction tandem solar cells, perovskite/Si dual-junction tandem solar cells, CdZnTe/Si dual-junction

Figure 14. Calculated 1-sun efficiency of III-V/Si triple-junction and dual-junction tandem solar cells, perovskite/Si dual-junction tandem solar cells, CdZnTe/Si dua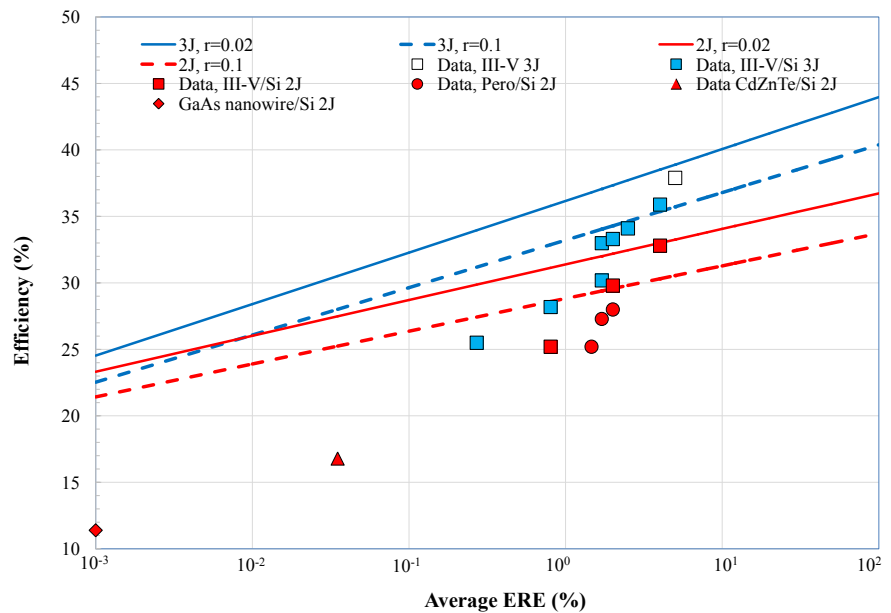l-junction tandem solar cell and GaAs nano-wire/Si dual-junction tandem cell as a function of ERE and $r_s + 1/r_{sh}$. White rectangular shows 37.9% efficiency InGaP/GaAs/InGaAs triple-junction tandem solar cell.

tandem solar cell and GaAs nano-wire/Si dual-junction tandem solar cell as a function of ERE and $r_s + 1/r_{sh}$.

At present, the III-V/Si triple-junction and dual-junction tandem solar cells have shown higher efficiency with 35.9% [33] and 32.8% [33] compared to perovskite/Si dual-junction tandem solar cells with efficiencies of 28.0% [21], CdZnTe/Si dual-junction tandem solar cell with an efficiency of 16.8% [34] and GaAs nano-wire/Si dual-junction tandem solar cell with an efficiency of 11.4% [35]. Such an efficiency difference is thought to be differences in material quality. For example, the external radiative efficiency values are 2% - 4% for III-V/Si tandem cells, 1% - 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, material quality is critical for further improvements in the performance of Si tandem solar cells. Although efficiency (35.9%) [33] of 4-terminal mechanical stacked InGaP/GaAs/Si triple-junction tandem solar cells is close to that (37.9%) [36] of InGaP/GaAs/InGaAs triple-junction cells, resistance loss is higher as shown in **Figure 14**. Resistance loss for the perovskite/Si tandem cells, CdZnTe/Si tandem cells and GaAs nano-wire/Si tandem cells are much higher compared to the III-V/Si tandem solar cells as s shown in **Figure 9**.

In this section, recent Japanese activities of III-V/Si tandem solar cells are presented. **Table 4** shows a summary of Japanese activities of InGaP/GaAs/Si tandem solar cells. The authors have demonstrated 28.2% [32] [37] with mechanically stacked InGaP/GaAs/Si triple-junction solar cell. Osaka City University also demonstrated 25.5% efficiency InGaP/GaAs/Si triple-junction solar cells

Table 4. Summary of Japanese activities of InGaP/GaAs/Si triple-junction tandem solar cells.

Eff.	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	Inter-connect	Note
25.5	0.25	2.847	10.94	81.83	Wafer bonding	OCU 2015
28.2 25.6 /2.6	0.95	2.33 0.52	13.7 7.6	80.1 65.2	4-terminal	TTI 2016
33.0	3.604	2.446 0.694	13.9 8.3	84.7 76.6	4-terminal	Sharp 2017
30.8	0.09538	3.03	12.72	80.0	PdNP array	AIST 2019

with 0.25 cm^2 area by using surface-activated bonding (SAB) [38]. Sharp Corporation has also attained 33.0% efficiency [39] with 3.604 cm^2 InGaP/GaAs/Si triple-junction solar cells by using the mechanical stack. Most recently, AIST has demonstrated a novel interconnect layer made of palladium nanoparticle (PdNP) between III-V and silicon that could be both optically transparent and electrically conductive, allow two-terminal configuration. A 30.8% efficiency [40] under 1-sun with InGaP/AlGaAs/Si triple-junction solar cells fabricated by using PdNP array-mediated bonding was demonstrated.

5. Recent Approaches for PV-Powered Vehicles

Table 5 shows that the progress of practical phase and development phase PV-powered vehicles [41]. Toyota Motor Co. released Prius equipped with 56 W multi-crystalline Si solar cell modules and new Prius PHV with Si HIT solar cells modules with 180 W into markets in 2010 and 2017, respectively. Other auto companies also have developed PV-powered vehicles, and some of them have announced that they will start selling the PV-powered vehicles in 2020 and 2021.

Most recently, Toyota has developed test car by using Sharp's high-efficiency In GaP/GaAs/InGaAs triple-junction solar cell modules (output power of 860 W, average cell efficiency of 34.9%) under the NEDO support [42] as shown in Figure 15. The daily driving range of 44.5 km is expected to be realized by using solar energy. Data collection and analysis are under driving test by using the Toyota Prius PHV test car.

We recently proposed a new static low concentrator which does not require tracking system for the automotive application. It is effective to reduce the cost of PV module by utilizing a concentrator because it can be reduced the total solar cell area. Since the installing a tracker on a vehicle roof is difficult, a static concentrator is suitable for the automotive application. Static concentrators that combined with III-V compound solar cells have many other advantages: 1) applicability of mounting on a three-dimensional curved surface, 2) robustness to partial shading, and 3) a shark-skin structure has advantage for aero-dynamics property. A high Voc can be attained thanks to the robustness to partial shading, allows a bypass diode to be equipped with each cell in the gap between cells in the module, and facilitates size reduction of the lens aperture.

Table 5. Status of practical phase and development phase PV-powered vehicles.

Auto company		Module	Output power	Driving range	Sales start year
TOYOTA https://global.toyota/jp/newsroom/toyota/27965888.html		Si (HIT)	180 W	~6.1 km/day	2017
HYUNDAI https://www.bbc.com/news/technology-49249884		Si	NA	NA	NA
LIGHTYEAR https://lightyear.one/		Si (IBC)	1000 W	~50 km/day	2021
SONO MOTORS https://sonomotors.com/		Si (IBC)	1204 W	~34 km/day	2020
Hanergy http://en.hanergythinfilmpower.com/index.html		GaAs	NA	NA	NA

Collaboration with Sharp and NEDO

Prius PHV

InGaP/GaAs/InGaAs 3-junction (Sharp)

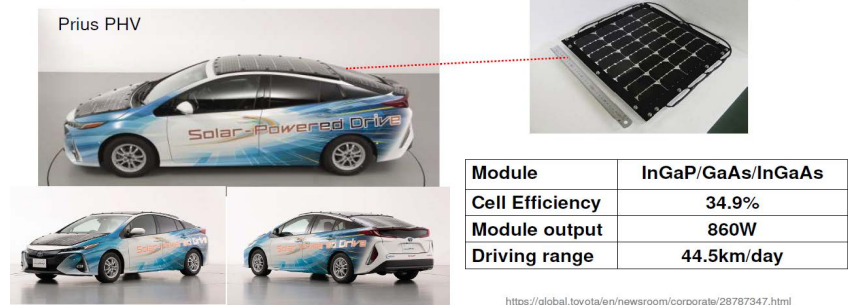| Module	InGaP/GaAs/InGaAs
Cell Efficiency	34.9%
Module output	860W
Driving range	44.5km/day

https://global.toyota/en/newsroom/corporate/28787347.html

Figure 15. Toyota Prius PHV demonstration car using InGaP/GaAs/InGaAs triple-junction solar cell module and characteristics.

Figure 16 shows the calculated results of the trends of annual power yield by III-V/Si tandem modules and crystalline Si modules as a function of concentration ratio [43] [44]. The crystalline Si module cannot be attained the target yield even with a considerable (4 m^2) roof area., while III-V/Si tandem module and static low concentrator module up to 4-suns concentration factor can generate the target value, which indicating that the cells are promising candidate for automotive applications.

We recently demonstrated aperture efficiency of 27.6% with the static low concentrator module combined with III-V based triple-junction solar cell [43] [44]. Figure 17 shows that the module has 99 solar cells (33 cells were connected in series, and three strings were connected in parallel) which were mounted on the circuit board. The low concentrated lens was aligned on each cell and silicone (sealing resin) was filled in the gap between the cell and lens. The module in which area is 41.2 cm^2 has a conversion efficiency of 27.6% under on-axis 1 sun illumination. The module efficiency can be improved by reducing optical and electrical losses of the concentrator, such as reflection at the interface of Air/PMMA (3.9%), reflection at PMMA/Silicone (0.7%), diode loss (0.5%), voltage mismatch (0.3%), and current mismatch (7.1%). It is expected that the module efficiency is reached to 30% by reducing the mismatching loss and optical losses.
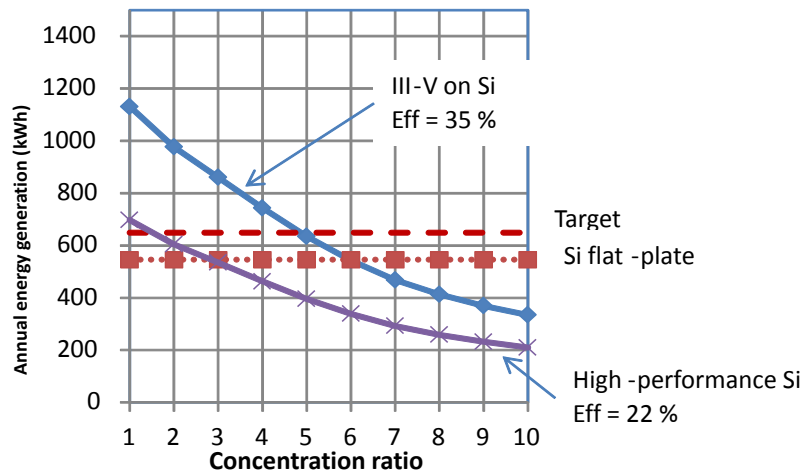
Figure 16. Trends of annual energy yield by III-V/Si tandem modules and crystalline Si modules as a function of concentration ratio.
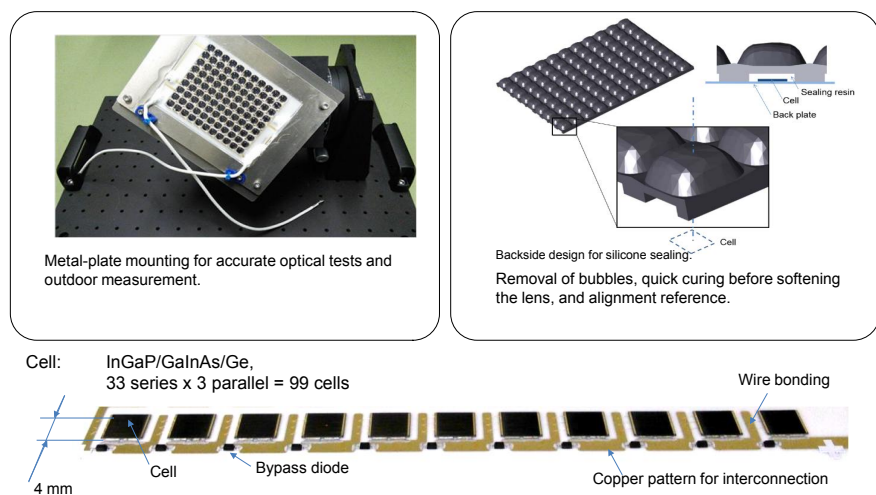

Figure 17. Photo of prototype static low concentrator module with III-V based triple-junction solar cell.

Figure 18(a) and **Figure 18(b)** show the schematic drawing of a new partial CPV with static low concentrator concept [45]. The concentrator "partially" focuses on a component of the sunlight energy toward high-efficiency triple-junction cells; the remaining portions are captured using low-cost Si cells. This concept can eliminate the inactive area and improve the conversion efficiency of the module by harvesting global sunlight in a full module aperture.

Figure 18(c) shows the prototype III-V/Si partial LCPV submodule with an area of 32×40 mm^2 [46]. The prototype flexible submodule composes of a 4×5 silicone lens array (each area 8×8 mm^2), 4×5 InGaP/GaInAs/Ge triple-junction cells (each area 4.05×4.57 mm^2), and a crystalline Si cell which is located underneath of the III-V cells. This submodule is a 4-terminal mechanical stack in which the silicone lens encapsulates the triple-junction solar cells atop the Si cell via a thin transparent glass substrate. Because module thickness should be as low
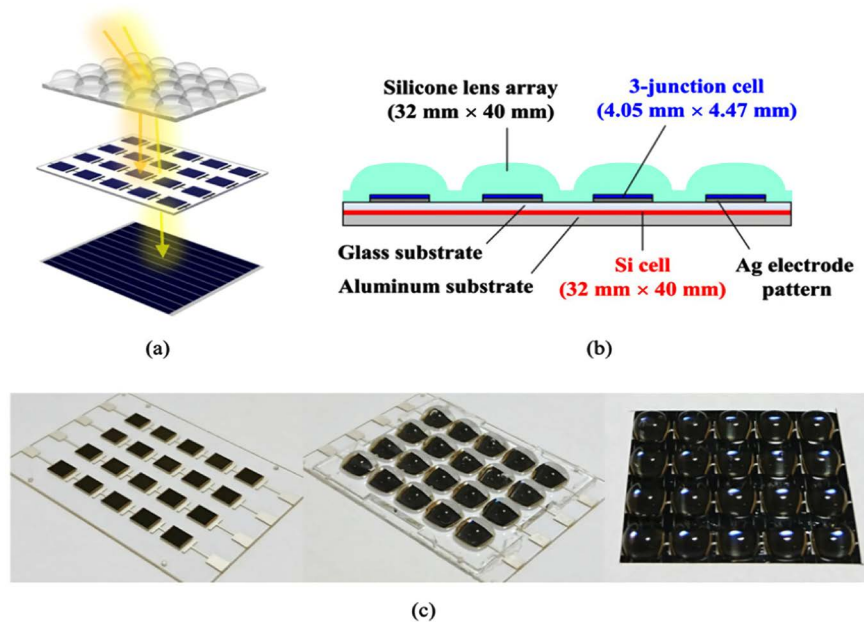
Figure 18. Prototype III-V/Si partial static low-concentrator submodule.

as possible for the automotive applications, the thickness of the assembled module was designed to approximately 6.0 mm. The measurement results show that the prototype module can potentially achieve up to 27.3% annual module efficiency, as projected from the actual daily submodule efficiency of 20.8% assuming state-of-the-art record cell efficiency.

6. Summary

Development of high-efficiency solar cell modules and new application fields are significant for the further development of photovoltaics (PV) and creation of new clean energy infrastructure based on PV. Especially, development of PV-powered EV applications is desirable and very important for this end. Efficiency impact on reducing CO_2 emission and increase in driving distance in PV-powered vehicles was shown in this paper. Development of high-efficiency solar cell modules with an efficiency of more than 30% is essential for PV-powered vehicle applications.

This paper presented analytical results developed by the authors for efficiency potential of various solar cells for choosing candidates of high-efficiency solar cell modules for automobile applications. As a result of the analysis, static low concentration PV and Si tandem solar cells such as III-V/Si tandem solar cells are thought to be some of their candidates. This paper also overviewed efficiency potential and recent activities of various Si tandem solar cells such as III-V/Si, II-VI/Si, chalcopyrite/Si, perovskite/Si and nanowire/Si tandem solar cells. Present status of Si tandem solar cells such as 35.9% for III-V/Si triple-junction, 32.8% for III-V/Si dual-junction, 28.0% for perovskite/Si dual-junction tandem solar cells was overviewed. The III-V/Si tandem solar cells are expected to have significant potential for various applications because of high efficiency with effi-

ciencies of more than 42% under 1-sun AM1.5 G, lightweight and low-cost potential. As a result of further development of Si tandem solar cell modules and creation of PV-powered vehicle market, cost reduction of modules for PV-powered vehicles will be realized. Recent results for our 28.2% efficiency and Sharp's 33% mechanically stacked InGaP/GaAs/Si triple-junction solar cells were also presented. Some approaches such as InGaP/GaAs/InGaAs triple-junction solar cell powered vehicle, static low concentrator III-V triple-junction cell modules and low-concentration static III-V/Si partial concentrator cell modules were also presented.

In summary, the authors have shown that solar modules for PV-powered vehicles have great ability to reduce CO_2 emission. Development of high efficiency (>30%), colored, and flexible modules is essential. Static concentrator PV, Si tandem PV and colored PV are attractive candidates for future car applications.

Acknowledgements

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] WBGU (German Advisory Council on Global Change) (2003) The World in Transition—Towards Sustainable Energy Systems. Earthsan, London.
http://www.wbgu.de

[2] Shell (2018) Sky Scenario Data 2018. http://www.shell.com/skyscenario

[3] NEDO (2018) Interim Report "PV-Powered Vehicle Strategy Committee".
http://www.nedo.go.jp/english/index.html

[4] Yamaguchi, M., Araki, K., Lee, K.-H., Kojima, N., Masuda, T., Kimura, K., Satou, A. and Yamada, H. (2017) Towards Creation of Mobility Society Using Solar Energy. *Proceedings of the* 5*th IEEE International Conference on Smart Energy Grid Engineering*, Oshawa, 14-17 August 2017, 394.
https://doi.org/10.1109/SEGE.2017.8052832

[5] International Energy Agency (2015) CO_2 Emissions from Fuel Combustion Highlights 2014 Edition.
https://www.iea.org/publications/freepublications/publication/CO$_2$EmissionsFromFuelCombustionHighlights2014.pdf

[6] Renewable Energy Institute (2018) Trends and Prospect of EV.
http://www.renewable-ei.org

[7] Kimura, K., Kudo, Y. and Sato, A. (2016) Techno-Economic Analysis of Solar Hybrid Vehicles Part 1: Analysis of Solar Hybrid Vehicle Potential Considering

Well-to-Wheel GHG Emissions. SAE Technical Paper 2016-01-1287.
https://doi.org/10.4271/2016-01-1287

[8] Hara, T., Shiga, T., Kimura, K. and Sato, A. (2016) Techno-Economic Analysis of Solar Hybrid Vehicles Part 2: Comparative Analysis of Economic, Environmental, and Usability Benefits. SAE Technical Paper 2016-01-1286.
https://doi.org/10.4271/2016-01-1286

[9] Japan Automobile Dealers Association.
http://www.jada.or.jp/data/month/m-brand-ranking

[10] CHAdeM Association (2016).
https://www.chademo.com/wp2016/wp-content/japan-uploads/QCkasyosuii.pdf

[11] Japanese Ministry of Land, Infrastructure, Transport, and Tourism (2015) Road Traffic Census. (In Japanese) http://www.mlit.go.jp/road/ir/ir-data/ir-data.html

[12] Agency for Natural Resources and Energy (Japanese Ministry of Economy, Trade, and Industry) (2014) Outline of the 2014 Annual Report on Energy. Energy White Paper 141.

[13] Masuda, T., Araki, K., Okumura, K., Urabe, S., Kudo, Y., Kimura, K., Nakado, T., Sato, A. and Yamaguchi, M. (2017) Static Concentrator Photovoltaics for Automotive Applications. *Solar Energy*, **46**, 523-531.
https://doi.org/10.1016/j.solener.2017.03.028

[14] Yamaguchi, M., Yamada, H., Katsumata, Y., Lee, K.-H., Araki, K. and Kojima, N. (2017) Efficiency Potential and Recent Activities of High-Efficiency Solar Cells. *Journal of Materials Research*, **32**, 3445-3457. https://doi.org/10.1557/jmr.2017.335

[15] Goetzberger, A., Luther, J. and Willek, G. (2002) Solar Cells: Past, Present, Future. *Solar Energy Materials and Solar Cells*, **74**, 1.
https://doi.org/10.1016/S0927-0248(02)00042-9

[16] Shockley, W. and Queisser, H.J. (1961) Detailed Balance Limit of Efficiency of p-n Junction Solar Cells. *Journal of Applied Physics*, **32**, 510.
https://doi.org/10.1063/1.1736034

[17] Yamaguchi, M., Lee, K.-H., Araki, K., Kojima, N., Yamada, H. and Katsumata, Y. (2018) Analysis for Efficiency Potential of High-Efficiency and Next-Generation Solar Cells. *Progress in Photovoltaics*, **26**, 543. https://doi.org/10.1002/pip.2955

[18] Green, M.A., Emery, K., Hishikawa, Y. and Warta, W. (2010) Solar Cell Efficiency Tables (Version 36). *Progress in Photovoltaics*, **18**, 346.
https://doi.org/10.1002/pip.1021

[19] Green, M.A., Emery, K., Hishikawa, Y., Warta, W. and Dunlop, E.D. (2016) Solar Cell Efficiency Tables (Version 45). *Progress in Photovoltaics*, **24**, 905.
https://doi.org/10.1002/pip.2788

[20] Green, M.A., Emery, K., Hishikawa, Y., Warta, W., Dunlop, E.D., Levi, D.H. and Ho-Baillie, A.W.H. (2017) Solar Cell Efficiency Tables (Version 50). *Progress in Photovoltaics*, **25**, 668. https://doi.org/10.1002/pip.2909

[21] Green, M.A., Dunlop, E.D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N. and Ho-Baillie, A.W.Y. (2020) Solar Cell Efficiency Tables (Version 55). *Progress in Photovoltaics*, **27**, 565. https://doi.org/10.1002/pip.3171

[22] Rau, U. (2007) Reciprocity Relation between Photovoltaic Quantum Efficiency and Electroluminescent Emission of Solar Cells. *Physical Review B*, **76**, Article ID: 085303. https://doi.org/10.1103/PhysRevB.76.085303

[23] Green, M.A. (2012) Radiative Efficiency of State-of-the-Art Photovoltaic Cells. *Progress in Photovoltaics*, **20**, 472. https://doi.org/10.1002/pip.1147

[24] Yao, J., Kirchartz, T., Vezie, M.S., Faist, M.A., Gong, W., He, Z., Wu, W.H., Troughion, J., Watson, T., Bryant, D. and Nelson, J. (2015) Quantifying Losses in Open-Circuit Voltage in Solution-Processable Solar Cells. *Physical Review Applied*, **4**, Article ID: 014020. https://doi.org/10.1103/PhysRevApplied.4.014020

[25] Green, M.A. (1998) Solar Cells. UNSW, Kensington.

[26] Singh, P. and Ravindra, N.M. (2012) Temperature Dependence of Solar Cell Performance—An Analysis. *Solar Energy Materials & Solar Cells*, **101**, 36-45. https://doi.org/10.1016/j.solmat.2012.02.019

[27] Yang, M., Araki, K. and Yamaguchi, M. unpublished data.

[28] Hishikawa, Y., Doi, T., Yamagoe, K., Ohshima, H., Takenouchi, T. and Yoshita, M. (2018) Voltage-Dependent Temperature Coefficient of the I-V Curves of Crystalline Silicon Photovoltaic Modules. *IEEE Journal of Photovoltaics*, **8**, 48. https://doi.org/10.1109/JPHOTOV.2017.2766529

[29] Yamaguchi, M., Araki, K., Lee, K.-H., Sato, D., Kojima, N., Nakamura, K., Ohshita, Y., Masuda, T., Satou, A., Yamada, K., Takamoto, T., Sato, T., Yamazaki, M. and Yamada, H. (2019) Solar Cells for Cars. 29*th NREL Si Workshop*, Winter Park, 4-7 August 2019.

[30] Ekins-Daukes, N. (2019) Investigation into the Effect of Colour on PV Efficiency. *IEA/PVPS Task* 17 *Expert Meeting*, Munich, 13-14 May 2019.

[31] Yamaguchi, M., Warabisako, T. and Sugiura, H. (1994) Chemical Beam Epitaxy as a Breakthrough Technology for Photovoltaic Solar Energy Application**s**. *Journal of Crystal Growth*, **136**, 29-36. https://doi.org/10.1016/0022-0248(94)90379-4

[32] Yamaguchi, M., Lee, K.-H., Araki, K. and Kojima, N. (2018) A Review of Recent Progress in Heterogeneous Silicon Tandem Solar Cells. *Journal of Physics D: Applied Physics*, **51**, Article ID: 133002. https://doi.org/10.1088/1361-6463/aaaf08

[33] Essig, S., Allebe, C., Remo, T., Geisz, J.F., Steiner, M.A., Horowitz, K., Barrud, L., Ward, J.S., Schnabel, M., Descoeudres, A., Young, D.L., Woodhouse, M., Despeisse, M., Ballif, C. and Tamboli, A. (2017) Raising the One-Sun Conversion Efficiency of III-V/Si Solar Cells to 32.8% for Two Junctions and 35.9 % for Three Junctions. *Nature Energy*, **2**, 17144. https://doi.org/10.1038/nenergy.2017.144

[34] Carmody, M., Mallick, S., Margetis, J., Kodama, R., Biegala, T., Xu, D., Bechmann, P., Garland, J.W. and Sivananthan, S. (2010) Single-Crystal II-VI on Si Single-Junction and Tandem Solar Cell. *Applied Physics Letters*, **96**, Article ID: 153502. https://doi.org/10.1063/1.3386529

[35] Yao, M., Cong, S., Arab, S., Huang, N., Povinelli, M.L., Cronin, S.B., Dapkus, P.D. and Zhou, C. (2015) Tandem Solar Cells Using GaAs Nanowires on Si: Design, Fabrication, and Observation of Voltage Addition. *Nano Letters*, **15**, 7217. https://doi.org/10.1063/1.3386529

[36] Sasaki, K., Agui, T., Naaido, K., Takahasi, N., Onitsuka, R. and Takamoto, T. (2013) Development of InGaP/GaAs/InGaAs Inverted Triple Junction Concentrator Solar Cell. *AIP Conference Proceedings*, **1556**, 22. https://doi.org/10.1063/1.4822190

[37] Yamaguchi, M., Lee, K.-H., Araki, K., Nakamura, K., Kojima, N. and Ohshita, Y. (2016) Recent Activities of III-V/Si Tandem Solar Cells. 20*th International Conference on Ternary and Multinary Compounds*, Halle, 5-9 September 2016. https://doi.org/10.1149/06904.0011ecst

[38] Shigekawa, N., Liang, J., Onitsuka, R., Agui, T., Juso, H. and Takamoto, T. (2015) Current-Voltage and Spectral-Response Characteristics of Surface-Activated-Bonding-Based InGaP/GaAs/Si Hybrid Triple Junction Cells. *Japanese Journal of Applied Physics*, **54**,

08KE03. https://doi.org/10.7567/JJAP.54.08KE03

[39] Takamoto, T., Juso, H., Ueda, K., Washio, H., Yamaguchi, H., Imaizumi, M., Sumita, T. and Nakamura T. (2017) IMM Triple-Junction Solar Cells and Module Optimized for Space and Terrestrial Conditions. *Proceedings of the 44th IEEE Photovoltaic Specialist Conference*, IEEE, New York, 975. https://doi.org/10.1109/PVSC.2017.8366097

[40] Makita, K., Mizuno, H., Tayagaki, T., Aihara, T., Oshima, R., Shoji, Y., Takato, H., Muller, R., Beutel, P., Lackner, D., Benick, J., Hermle, M., Dimroth, F. and Sugaya T. (2019) III-V/Si Multijunction Solar Cells Reaching 30% Efficiency Using Smart Stack Technology with Pd Nanoparticle Array. *Progress in Photovoltaics*, **28**, 16-24. https://doi.org/10.1002/pip.3200

[41] Yamaguchi, M., Masuda, T., Araki, K., Sato, D., Lee, K.-H., Kojima, N., Nakamura, K., Ohshita, Y., Satou, A., Yamada, K., Nakadou, T., Takamoto, T., Sato, T., Yamazaki, M., Hasegawa, M. and Yamada, H. (2019) Some Approaches of PV-Powered Vehicles Applications. In: *Proceedings of the 36th European Photovoltaic Solar Energy Conference and Exhibition*, WIP, Munich, 1787.

[42] NEDO, Sharp, Toyota (2019) Press Release, July 4. https://global.toyota/en/newsroom/corporate/28787347.html

[43] Araki, K., Nakamura, K., Lee, K.-H., Kamioka, T., Wang, Y.-C., Kojima, N., Ohshita, Y. and Yamaguchi, M. (2017) Design of a Lateral III-V/Si Hybrid Module. *Proceedings of the 44th IEEE Photovoltaic Specialists Conference*, IEEE, New York, 2498-2501. https://doi.org/10.1109/PVSC.2017.8366540

[44] Masuda, T., Araki, K., Okumura, K., Urabe, S., Kudo, Y., Kimura, K., Nakado, T., Sato, A., Lee, K.-H. and Yamaguchi, M. (2017) Solar Powered Vehicles with Static Concentrator Photovoltaics. *33rd European Photovoltaic Solar Energy Conference*, Amsterdam, 25-29 September 2017.

[45] Sato, D., Lee, K.-H., Araki, K., Yamaguchi, M. and Yamada, N. (2019) Design and Evaluation of a III-V/Si Partial CPV Module for Maximization of Power Generation per Unit Module Area. *IEEE Journal of Photovoltaics*, **9**, 147-153. https://doi.org/10.1109/JPHOTOV.2018.2877015

[46] Sato, D., Lee, K.-H., Araki, K., Masuda, T., Yamaguchi, M. and Yamada, N. (2019) Design of Low-Concentration Static III-V/Si Partial CPV Module with 27.3% Annual Efficiency for Car-Roof Application. *Progress in Photovoltaics*, **27**, 501-510. https://doi.org/10.1002/pip.3124