High-efficiency Si Tandem Solar Cells and Modules for Vehicle Integrated Photovoltaics

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Outline

1. Introduction
2. Impact of High-efficiency Solar Modules on Reduction in CO$_2$ Emission, Charging Cost Saving and Driving Distance Increase of Electric Vehicles
3. High-efficiency and Low-cost Potential of Si Tandem Solar Cells
4. Our Recent Approaches on Si Tandem Solar Cells and Modules
5. Summary
1. Introduction
ITRPV scenario for global cumulative PV installations
(International Technology Roadmap for PV, itrpv.vdma.org)
For realizing such a vision towards creation of future clean energy infra-structures, we need

1. to develop high performance, low cost and highly reliable PV materials, cells, modules and systems,

2. to develop smart energy management including regulations, and self-consumption in cooperation with storage battery technologies,

3. to develop new application fields such as automobile and agriculture applications towards the creation of future clean energy infrastructures.
For realizing such a vision towards creation of future clean energy infra-structures, we need

1. to develop high performance, low cost and highly reliable PV materials, cells, modules and systems,
2. to develop smart energy management including regulations, and self-consumption in cooperation with storage battery technologies,
3. to develop new application fields such as automobile and agriculture applications towards the creation of future clean energy infrastructures.
2. Impact of High-efficiency Solar Modules on Reduction in CO$_2$ Emission, Charging Cost Saving and Driving Distance Increase of Electric Vehicles
CO₂ emission per 1km driving for various vehicles in Japan and USA.


CO₂ Emission in Japan

Breakdown of CO₂ emissions in transport sector in Japan:

- Total CO₂ emissions 1,064 million tons (FY2021)
- Industry 35.1%
- Residential 14.7%
- Commercial 17.9%
- Transport 17.4%
- Other 15.0%

- Private passenger cars 44.3%
- Commercial trucks 23.0%
- Private trucks 16.8%
- Aviation 3.7%
- Rail 4.1%
- Buses 1.6%
- Taxis, Dometic shipping 0.7%
CO$_2$ emission per 1km driving for various vehicles in Japan, USA and China.


M. Yamaguchi et al., Energy and Power Engineering 12, 375 (2020).
Changes in cumulative registration number of Nissan LEAF (BEV) and number of quick chargers installed.


M. Yamaguchi et al., Energy and Power Engineering 12, 375 (2020).
Prediction of a number of PV-powered vehicles


Large market growth of PV and transport sector use in the USA

Future Growth to Drive Decarbonization

The U.S. Electric Grid in 2020

- 2020 Generation Mix
  - Fossil Fuels
  - Other non-Carbon
  - Solar

- 3,800 TWh
- 1.45 Gt CO₂/year

Solar in 2020: 3% of electricity demand, 80 GW_{AC} installed

95% Decarbonized Grid in 2035

- 2035 Generation Mix
- 4,900 TWh
- 0.1 Gt CO₂/year

Solar: 40% of electricity demand, 1,000 GW_{AC} installed

Decarbonized Grid in 2050

- 2050 Generation Mix
- 6,700 TWh
- Zero Grid Emissions

Solar: 45% of electricity demand, 1,600 GW_{AC} installed

3,000 GW_{AC} in decarbonized energy system

End Uses
- Buildings
- Industry
- Transportation

Becca Jones-Albertus, presented at the 49th IEEE PVSC, Philadelphia, June 2022
PV efficiency and cost impact on PV-EV applications estimated from the survey reports.

Necessity of high-efficiency PV modules for VIPV

How to install 800 W modules?

A. Roof/hood (~2.5 m²)
   - High efficiency module
   - III-V cells + concentrator

B. Roof/hood/side (~5.0 m²)
   - Module eff ≈ 20%
   - Film module

http://solarcellcentral.com/solar_page.html

## Comparison of Toyota Prius and Nissan Van demonstration cars

<table>
<thead>
<tr>
<th></th>
<th>Toyota Prius demonstration car</th>
<th>Nissan Van demonstration car</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Photo</strong></td>
<td><img src="image1" alt="Toyota Prius" /></td>
<td><img src="image2" alt="Nissan Van" /></td>
</tr>
<tr>
<td><strong>Vehicle</strong></td>
<td>PHEV</td>
<td>BEV</td>
</tr>
<tr>
<td><strong>Solar Cell</strong></td>
<td>InGaP/GaAs/InGaAs 3-junction solar cell</td>
<td>InGaP/GaAs/InGaAs 3-junction solar cell</td>
</tr>
<tr>
<td><strong>Module efficiency</strong></td>
<td>More than 30%</td>
<td>More than 30%</td>
</tr>
<tr>
<td><strong>Installed area</strong></td>
<td>Roof, hood, back door</td>
<td>Roof, hood, rear gate</td>
</tr>
<tr>
<td><strong>Output power</strong></td>
<td>860 W</td>
<td>1150 W</td>
</tr>
<tr>
<td><strong>Battery capacity</strong></td>
<td>8.8 kWh</td>
<td>40 kWh</td>
</tr>
<tr>
<td><strong>Electric mileage</strong></td>
<td>~9.35 km/kWh</td>
<td>~6.6 km/kWh</td>
</tr>
</tbody>
</table>

Test driving of the Toyota Prius PHV demonstration car at the Tokyo Ginza, Nov. 15, 2019.
Calculated results for changes in daily driving distance of PV-powered vehicles as a function of VIPV peak power in comparison with calibrated actual data for various PV-powered vehicles.

Effects of introduction of high-efficiency solar cell modules into EVs upon reduction in CO₂ emission were analysed. Average CO₂ emission intensity $C_{IEV}$ for EVs reported is 462 g-CO₂ e/kWh. EV usage CO₂ emission $C_{EEV}$ is expressed by

$$C_{EEV}[g-CO_2 \text{ e/km}] = C_{IEV}[g-CO_2 \text{ e/Wh}]E_{CEV}[Wh/km]) = C_{IEV}[g-CO_2 \text{ e/Wh}]/EM[km/Wh]), \quad (1)$$

where $E_{CEV}$ is the EV energy consumption and $EM$ is the electric mileage.

On the other hands, CO₂ emission $C_{EPV-production}$ for PV-production is given by

$$C_{EPV-production}[g-CO_2 \text{ e/km}] = P_{pv}[W]C_{IPV}[g-CO_2 \text{ e/W}]/(DD \text{ [km/day]}\tau_{PV}[years]), \quad (2)$$

where $P_{pv}$ is the module output power, $C_{IPV}$ is the carbon intensity per unit W, DD is the driving distance, and $\tau_{PV}$ is the lifetime for PV modules.

In this study, 1,008 g-CO₂ e/W was assumed as $C_{IPV}$ according to the reference and 15 years were assumed as $\tau_{PV}$ because of PV-powered vehicle applications. The PV-EV usage CO₂ emission $C_{EPV-EV}$ is expressed by

$$C_{EPV-EV}[g-CO_2 \text{ e/km}] = C_{EEV}[g-CO_2 \text{ e/km}] + C_{EPV-production}[g-CO_2 \text{ e/km}]. \quad (3)$$

Changes in cumulative frequency of passenger cars in Japan as a function of daily mileage reported in the reference (Hara et al.) and approximation curve.

Driving distance DD was estimated by using the following equation:

\[ DD[km/day] = SI[kWh/m^2/day] \times PR \times \eta[\%] \times 0.01A [m^2] \times EM[km/kWh], \tag{5} \]

where SI is the solar irradiance, PR the performance ratio of PV system and 0.739 was used as the PR in this case, A is the area of solar cell module and 3 m² was used as A this time, and EM is the electric mileage.

In the calculation, sharing ration of EV mode and PV mode for PV-EV was estimated by driving distance DD and eqs. (1) – (5).
Calculated results for reduction ratio of CO$_2$ emission of PV-EV installed with solar cell modules with different efficiencies as a function of electric mileage EM.

M. Yamaguchi et al., IEEE J-PV 13, 343 (2023).
Electricity cost saving for EV charging by usage of PV was analysed in this study. EV energy consumption EC is given by

$$EC \ [\text{kWh/year}] = DD \ [\text{km/year}] / EM \ [\text{km/year}]. \ (6)$$

Charging electricity cost CC of EV charging is given by

$$CC \ [\$/\text{year}] = EC \ [\text{kWh/year}] \times EP \ [\$/\text{kWh}], \ (7)$$

where EP is the household electricity and is $0.207/\text{kWh}$ in Japan in 2020. PV-EV cost saving $\Delta CS_{\text{PV-EV}}$ was calculated by using the following equation

$$\Delta CS_{\text{PV-EV}} \ [\$/\text{year}] = -\Delta E_{\text{grid}} \ [\text{kWh/year}] \times EP \ [\$/\text{kWh}]. \ (8)$$
Calculated results for charging electricity cost of EV and PV-EV as a function of electric mileage by assuming 30 km/day as average daily driving distance.

Calculated results for driving distance of vehicles powered by various Si tandem solar cells and III-V 3-junction tandem solar cells and module as a function of cell and module efficiency and temperature coefficient (TC) in comparison with estimated values of vehicles powered by various solar cells and module and actual driving distance calibrated of the Prius 2019 powered by 3-junction solar cell module and the Sono Motors Sion powered by back-contact Si solar cell module.

Driving distance (km/day) vs. Global horizontal irradiance (kWh/m²/day)

- EM = 6 km/kWh
- EM = 8 km/kWh
- EM = 10 km/kWh

Measured data

Average daily driving distance (17.0 km) has been demonstrated in Nagoya.

Calculated and actual driving distance for the Toyota Prius demonstration car with various EMs as a function of solar irradiance (GHI).

Kings’s expression for temperature rise: \( \Delta T = T_m - T_0 = SI*\exp[a + b*v] \)

(a) Temperature rise (measured temperature above ambient temperature) of Si module and GaAs module in the case of wind speed of 0.75-1.25 m/sec and Si module in the case of 3 m/sec as a function of solar irradiation, (b) temperature rise of crystalline Si solar cell modules with and without insulation as a function of wind speed.

Our data for the temperature rise of solar cell modules versus solar irradiance in the 3 cases of average wind speed.

\[ \Delta T_L = T_m - T_0 = c \times \exp[d \times v] = -9 \times \exp[-0.16v] \]
\[ \Delta T/SI = \exp[a + b \times v] = \exp[-2.7 - 0.17v] \]

(a) temperature rise of solar cell modules under zero solar irradiance \( \Delta T_L \) versus wind speed, (b) temperature rise \( \Delta T \) relative to solar irradiance \( SI \) of solar cell modules under normal solar irradiation conditions versus wind speed.

Total temperature rise $\Delta T_T$ of solar cell modules is given by

$$\Delta T_T = \Delta T_L + \Delta T = c \times \text{EXP}[d \times v] + \text{SI} \times \text{EXP}[a + b \times v],$$  \(1\)

where $T_m$ is the module temperature [°C], $T_0$ is the ambient temperature [°C], SI is the solar irradiation incident on the module surface [W/m²], and $v$ is the wind speed [m/sec].

$a$ is the empirically-determined coefficient establishing the upper limit for module temperature at low wind speed and high solar irradiation,

$b$ is the empirically-determined coefficient establishing the rate at which module temperature decreases as wind speed increases,

$c$ is the empirically-determined coefficient establishing the upper limit for module temperature decrease at low wind speed under zero solar irradiation

$d$ is the empirically-determined coefficient establishing the rate at which module temperature decreases as wind speed decreases.

Empirically determined coefficients were used to predict module temperature for various solar cell modules including our solar cell module.

<table>
<thead>
<tr>
<th>Module type</th>
<th>Mount</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si module</td>
<td>close mount</td>
<td>-3.05</td>
<td>-0.25</td>
<td>0</td>
<td></td>
<td>Wheeler et al.</td>
</tr>
<tr>
<td>Slide 7 (a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaAs module(a)</td>
<td>close mount</td>
<td>-3.05</td>
<td>-0.5</td>
<td>0</td>
<td></td>
<td>Wheeler et al.</td>
</tr>
<tr>
<td>Si module under wind speed with 3m/sec (a)</td>
<td>close mount</td>
<td>-3.05</td>
<td>-0.25</td>
<td>0</td>
<td></td>
<td>Yukawa et al.</td>
</tr>
<tr>
<td>Si module</td>
<td>insulated</td>
<td>-2.53</td>
<td>-0.135</td>
<td>0</td>
<td></td>
<td>Yukawa et al.</td>
</tr>
<tr>
<td>Slide 7 (b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si module (b)</td>
<td>Standard (close mount)</td>
<td>-3</td>
<td>-0.17</td>
<td>0</td>
<td></td>
<td>Yukawa et al.</td>
</tr>
<tr>
<td>Our module</td>
<td>insulated</td>
<td>-2.7</td>
<td>-0.17</td>
<td>-9</td>
<td>-0.6</td>
<td>This study</td>
</tr>
</tbody>
</table>

Driving distance DD was estimated by using the following equation:

\[ DD[\text{km/day}] = SI[\text{kWh/m}^2/\text{day}] \times SE \times \eta[\%] \times (1 - TC \times \Delta T) \times A[\text{m}^2] \times EM[\text{km/kWh}], \quad (2) \]

where SI is the global solar irradiation, SE is the efficiency of the PV system (according to our previous study, 0.739 was used in this study), \( \eta \) is the efficiency of the solar cell module, TC is the temperature coefficient of solar cell module, \( \Delta T \) is the temperature rise of solar cell module, A is the area of solar cell module, and EM is the electric mileage of the PV-EV.

Calculations were carried out by using eqs. (2) and (1), and parameters shown in previous table and assuming -0.3%/°C as the temperature coefficient TC of VIPV modules.

In the calculation, 1 kW was used as the output power of the VIVP module, and 10 km/kWh was assumed as EM.
World map and the major cities analyzed in the world.

M. Yamaguchi et al., presented at the 50\textsuperscript{th} IEEE PVSC Puerto Ric., June 2023.
Examples for (a) daily average global solar irradiation [kWh/m²/day], monthly maximum, average, and minimum ambient temperature [°C], (b) average solar irradiance [kW/m²] and average wind speed [m/sec] in the major cities in the world.  

Annual driving distances calculated by considering power loss due to the temperature rise of solar cell modules and the effects of wind speed for PV-EV installed with 1 kW VIVP module and EM of 10 km/kWh under driving in major cities in the world.

Annual driving ranges were estimated by considering the effects of temperature rise of VIPV modules for the Toyota Prius and Nissan Van demonstration cars and the actual annual driving range.

<table>
<thead>
<tr>
<th>Car</th>
<th>Location</th>
<th>Annual driving range (km)</th>
<th>Additional power loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Estimated range without temperature rise</td>
<td>Estimated range with temperature rise</td>
</tr>
<tr>
<td>Toyota Prius test car</td>
<td>Nagoya</td>
<td>9,718</td>
<td>9,114</td>
</tr>
<tr>
<td>(VIPV power =860W, EM =9.35km/kWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nissan Van test car</td>
<td>Yokohama</td>
<td>9,054</td>
<td>8,502</td>
</tr>
<tr>
<td>(VIPV power =1150W, EM =6.6km/kWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Power loss was calculated by using eqs. (2) (3) and maximum outside temperature $T_{\text{max}}$.

\[ EM = EM_0 (19 - T_{\text{max}}) \times (\pm 0.4) \text{ [km/kWh/°C]}, \] (2)

\[ EM = EM_0 (19 - T_{\text{max}}) \times (\pm 0.2) \text{ [km/kWh/°C]}, \] (3)

where $EM_0$ is the original EM of PV-EV in the case of no operation of air-conditioners. Such values are fitted with experimental values, although the reference value is about -0.25 km/kWh/°C.

Reduction ratio of driving distance of the Toyota Prius demonstration car and the Nissan Van demonstration car during one year driving due to usage of air-conditioner versus maximum outside temperature during one month driving and calculated reduction ratio of driving distance.

M. Yamaguchi et al., presented at the 40th EU-PVSEC Lisbon, Sep. 2023.
Driving distance of PV-EV in the major cities in Japan and the world as a result of usage of air-conditioner was analyzed by using eq. (4) and (5).

\[ DD[km/day] = SI[kwh/m^2/day] \times SE \times \eta \% \times A[m^2] \times EM_0(19-T_{max}) \times (\pm 0.2) \text{[km/kWh/°C]} , (4) \]

\[ DD[km/day] = SI[kwh/m^2/day] \times SE \times \eta \% \times A[m^2] \times EM_0(19-T_{max}) \times (\pm 0.4) \text{[km/kWh/°C]} , (5) \]

where 1kW was used as output power of VIVP module, 0.739 was assumed as SE and 10 km/kWh was assumed as EM_0.
Japan map- Sapporo, Sendai, Niigata, Tokyo, Yokohama, Nagoya, Osaka, Hiroshima. Kochi, Miyazaki

M. Yamaguchi et al., presented at the 40th EU-PVSEC Lisbon, Sep. 2023.
Daily average global solar irradiation [kWh/m²/day] and monthly maximum, average and minimum ambient temperature [°C] in the major cities in Japan.

M. Yamaguchi et al., presented at the 40th EU-PVSEC Lisbon, Sep. 2023.
Annual driving distance calculated by considering power loss due to usage of air-conditioner for PV-EV installed with 1kW VIVP module and drove in major cities in Japan.

M. Yamaguchi et al., presented at the 40th EU-PVSEC Lisbon, Sep. 2023.
Annual driving distance calculated by considering power loss due to usage of air-conditioner for PV-EV installed with 1kW VIVP module and drove in major cities in the world.

M. Yamaguchi et al., presented at the 40th EU-PVSEC Lisbon, Sep. 2023.
Power loss analytical results of some factors for Toyota and Nissan demonstration cars.

M. Yamaguchi et al., presented at the 40th EU-PVSEC Lisbon, Sep. 2023.
3. High-efficiency and Low-cost Potential of Si Tandem Solar Cells
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 shipped in 2009, and those for Toyota New Prius shipped in 2017, and module efficiency and module cost targets of PV-EV.

M. Yamaguchi et al., Energy and Power Engineering 12, 375 (2020).
Comparison of module cost as a function of module production volume for a III-V tandem, high speed deposition, Si tandem and concentrator solar cell modules reported by the authors in comparison with cost analytical results for high speed deposition and Si tandem reported by NREL.

M. Yamaguchi et al., Prog. Photovolt. DOI:10.1002/pip3343.
Examples for the layer structure of a perovskite/Si dual-junction solar cell structure with pyramids on the rear (left) and a GaInP/GaAs/Si triple-junction solar cell that uses a nanostructured resist grating as a diffusor on the back (right).

Mechanical Stacked GaInP/GaAs/Si 3-J solar cell (35.9%)

Wafer bonded GaInP/GaInAsP/Si 3-J solar cell (35.9%)
P. Schygulla et al., Prog. Photovolt. 30, 869 (2022).

Direct-grown GaInP/GaAs/Si 3-J solar cell (25.9%)
M. Feifel et al., Solar RRL 5, 2000763 (2021)
Chronological efficiency improvements of III-V/Si 3-junction, 2-junction and perovskite/Si 2-junction solar cells in comparison with those of III-V 3-junction solar cells under 1-sun condition.

Open-circuit voltage of solar cells is expressed by
\[ V_{oc} = V_{oc:rad} + \frac{(kT/q)\ln(ERE)}{\ln(ERE)} \]  
(9)
where \( k \): Boltzmann constant, \( T \): temperature, \( q \): elementary charge.

\( V_{oc:rad} \) is the radiative open-circuit voltage and we use \( V_{oc:rad} \) values in our analysis:
Values of \( E_g/q - V_{oc, rad} \) used are 0.23V for CIGS, CdTe, 0.26V for Si, 0.28V for III-V compounds and perovskite.

The second term on the right-hand side of eq. (9) 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 \( V_{oc} \): loss:
\[ \Sigma(V_{oc,n} - V_{oc,rad,n})/n = \frac{(kT/q)\ln(ERE_{ave})}{\ln(ERE_{ave})} \]  
(10)
The resistance loss of a solar cell is estimated from the measured fill factor. The ideal fill factor \( FF_0 \), defined as the fill factor without any resistance loss, is estimated by
\[ FF_0 = \frac{(voc - \ln(voc + 0.71))/(voc + 1)}{V_{oc}/(nkT/q)} \]  
(12)

The measured FF can be related to the series resistance and shunt resistance:
\[ FF \approx FF_0(1 - r_s)(1 - r_{sh}^{-1}) \approx FF_0(1 - r_s - r_{sh}^{-1}) = FF_0(1 - r), \]  
(13)
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
\[ R_{CH} = V_{oc}/J_{sc}, \]  
(14)
r is the total normalized resistance defined by \( r = r_s + r_{sh}^{-1} \).

Calculated 1-sun efficiency of various Si tandem solar cells and III-V 3-junction solar cells including our results for III-/Si 3-junction tandem solar cells as a function of ERE and resistance loss $r_s + 1/r_{ss}$. White rectangular shows InGaP/GaAs/InGaAs triple-junction tandem solar cells.

Analytical results for non-radiative recombination, optical and resistance losses of various Si tandem solar cells in comparison with those of single-junction and III-V 3-junction and 2-junction solar cells. M. Yamaguchi et al., Prog. Photovolt (2024). DOI: 10.1002/pip.3780.
4. Our Recent Approaches on Si Tandem Solar Cells and Modules
Requirements of Solar Cell Modules for PV-powered Vehicles

• **High Performance**
  
  High efficiency
  
  Good temperature coefficient
  
  Good properties under low illumination intensity

• **Low Cost**

• **3 Dimensional Curvature**

• **Color Variation**
Calculated results for temperature coefficients of crystalline Si, GaAs and III-V compound triple-junction cells and modules as a function of its conversion efficiencies of the cells and modules in comparison with reported values and estimated values.

Reported values temperature coefficients of crystalline Si solar cell modules as a function of module efficiency.

A structure of Si heterojunction solar cell fabricated.

M. Yamaguchi et al., presented at the 40th EU-PVSEC, Lisbon, Sep. 18-22, 2023
A structure, photo and properties of Si hetero-junction solar cell and 4-terminal InGaP/GaAs/Si 3-junction solar cell.

Calculated efficiencies of crystalline Si solar cells as a function of external radiative efficiency (ERE) in comparison with realized efficiencies of Si solar cells reported by UNSW, Panasonic, Kaneka, Longi and authors (TTI).
Changes in open-circuit voltage Voc of SHJ solar cells by Kaneka, Longi and the authors as a function of minority-carrier lifetime.

Comparison of the measured and simulated minority carrier lifetimes as a function of excess carrier density for our two cases after surface passivation and IWO deposition.
Calculated efficiencies of III-V 2-junction solar cells as a function of external radiative efficiency (ERE) in comparison with realized efficiencies of III-V 2-junction upper solar cells for III-V/Si 3-junction tandem solar cells reported by the authors, Sharp including this study, NREL & EPFL and FhG-ISE in comparison with those of III-V 2-junction solar cells reported by LG and NREL.
A photo of new record efficiency InGaP/GaAs/Si 3-junction solar cell module and I–V charactersitics of InGaP/GaAs upper 2-junction solar cell module and Si bottom solar cell module.

M. Yamaguchi et al., presented at the 40th EU-PVSEC, Lisbon, Sep. 18-22, 2023
The characteristic solar cell module parameters confirmed by the AIST.

<table>
<thead>
<tr>
<th></th>
<th>Area (cm²)</th>
<th>Isc (A)</th>
<th>Voc (V)</th>
<th>FF (%)</th>
<th>Pm (W)</th>
<th>Module Efficiency (%)</th>
<th>Tandem Cell Module Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaP/GaAs 2J top cell module</td>
<td>775</td>
<td>1.245</td>
<td>20.29</td>
<td>86.5</td>
<td>21.85</td>
<td>28.17</td>
<td></td>
</tr>
<tr>
<td>Si bottom cell module</td>
<td>775</td>
<td>1.927</td>
<td>2.831</td>
<td>73.0</td>
<td>4.25</td>
<td>5.49</td>
<td>33.66</td>
</tr>
</tbody>
</table>
Changes in conversion efficiency of Si, GaAs, CdTe, perovskite single-junction solar cells and modules, and III-V/Si 3-junction and perovskite/Si 2-junction tandem solar cell and modules versus area of solar cells and modules.

Changes in average external radiative efficiency ERE for III-V multi-junction, III-V/Si tandem and perovskite/Si tandem solar cells and modules as a function of number of junctions.

M. Yamaguchi et al., presented at the 40th EU-PVSEC, Lisbon, Sep. 18-22, 2023
Changes in fill FF for III-V multi-junction, III-V/Si tandem and perovskite/Si tandem solar cells and modules as a function of number of junctions.

M. Yamaguchi et al., presented at the 40th EU-PVSEC, Lisbon, Sep. 18-22, 2023
New record efficiency (33.9%) perovskite/Si 2-junction tandem solar cell by Longi.
(J. Liu et al., PVSEC-34, Shenzhen, China, Nov. 6-10, 2023)
4T perovskite/Si-PERC 2-junction tandem solar cell (certified: 28.5% @64 cm²) and perovskite/Si-HBC 2-junction tandem solar cell (in-house measurement: 30.8% @64 cm²) by Kaneka.

(M. Kanematsu et al., PVSEC-34, Shenzhen, China, Nov. 6-10, 2023)
Changes in average ERE (external radiative efficiency) and fill factor of Si, GaAs, CdTe, perovskite single-junction solar cells and modules, and III-V/Si 3-junction and perovskite/Si 2-junction tandem solar cell and modules versus area of solar cells and modules.
Summary

This paper presented effectiveness of high-efficiency solar cell modules from point-views of driving distance, reduction in CO₂ emission with 55-70 % reduction and saving EV charging cost with $170-250/year.

The Si tandem solar cells are expected to have significant potential for PV-powered vehicle applications because of high efficiency with efficiencies of more than 42% under 1-sun AM1.5 G, lightweight and low-cost potential.

Most recently, the authors have achieved 35.8% efficiency with InGaP/GaAs/Si 3-junction tandem solar cell (area of 23 cm²) and new record efficiency 33.7% with 3-junction tandem solar cell module (area of 775 cm²).

It is summarized that the III-V/Si 3-junction solar cell modules have potential of driving distance of more than 30 km/day average and more than 50 km/day on a clear day.
A review of recent progress in heterogeneous silicon tandem solar cells

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Multi-junction solar cells paving the way for super high-efficiency

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Thank you very much!
Analytical results of various power losses of SEV according to test driving by Toyota and Nissan test cars.

M. Yamaguchi et al., to be presented at the 41st EU-PVSEC, Vienna, Austria, Sep. 2024.