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Topical Review for Vehicle Integrated Photovoltaics

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Abstract

Vehicle integrated Photovoltaic (VIPV)-powered vehicles are expected to play a critical role in a future carbon neutrality society because it has been reported that the VIPVs have a great ability to reduce CO_2 emission from the transport sector. Development of high-efficiency, low-cost, highly reliable solar cell modules is very important for VIPV. This paper presents a topical review for the VIPV. In this paper, impacts of high-efficiency solar cell modules on increases in electric vehicle (EV) driving distance, reducing CO_2 emission and charging cost saving of EV powered by VIPV are shown. The paper also overviews development of high-efficiency VIPV modules and discusses about reliability, partial shading 3-dimensional curvature and color variations of VIPV modules. Future prospects for VIPV modules are also presented in this paper.

Keywords

Vehicle Integrated Photovoltaics, Solar-Powered Vehicles, High-Efficiency Modules, Driving Distance, CO_2 Emission Reduction, Colour Variation, Partial Shading

1. Introduction

Development of the solar-powered electric vehicles (SEV) [1]-[11] is desirable and very important in order to create a new clean energy society where the carbon neutrality is realized. Even in automobile sector, reducing CO_2 emission is a critical challenge for contributing to sustainable development. Although BEV (battery-powered electric vehicle) has an advantage for less CO_2 emission compared to the other vehicles, further reduction in CO_2 emission is necessary since the cars still emit a large amount of CO_2 for the driving. On the other hand, the calculated results show that the vehicle integrated photovoltaics (VIPV) can make a significant reduction in CO_2 emission from 50% to 75% [5]. In order to enhance recognizing the SEV as major clean vehicles and to create a clean energy society based on PV, clarifying values of SEV and development of high-efficiency, low-cost, light-weight, 3-demensional curved applicable and colorful VIPV modules and other technologies are necessary.

This paper presents a topical review for the VIPV and shows effectiveness of high-efficiency VIPV modules upon driving distance, reduction in CO_2 emission and charging cost saving of EV. This paper overviews development of high-efficiency VIPV modules and discusses about reliability, partial shading, curved surface, and color variation of VIPV modules. Perspective for VIPV modules is also presented.

2. Trends in SEV and VIPVs

Vehicle-integrated photovoltaics (VIPV) are classified into the following three types depending on how the power generated by the VIPV panels is used. 1) a system to operate the ventilation fan, 2) a system to supply power to the auxiliary battery, and 3) a system to charge the main battery for driving. **Figure 1** shows the classification and history of commercially available vehicles equipped with PV panels.

Vehicles that fall under 1) have a long history, and examples include the Mazda Sentia (released in 1991) and the Audi A6 and A8 (released in 1993). These vehicles were equipped with PV panels on their sunroofs with a rated output of around 10 W, and the power generated by the PV panels was primarily used to drive a fan to ventilate the interior of the vehicle.

In the 1990s, many European car manufacturers, including Volkswagen and Mer cedes, sold similar systems. Toyota Motor Corporation's third-generation Prius, released in 2009, was also equipped with a similar solar power generation system.

Vehicles that fall under 2) include Nissan Motor's Leaf (released in 2010) and Xpeng P5 (released in 2021). In these vehicles, the power generated by the onboard PV panels is charged into an auxiliary battery (lead-acid battery) and used to operate things such as navigation and air conditioning.

In this way, VIPV panels have a long history, but until recently, vehicles that use the power generated by VIPV panels for driving energy had not been sold. The Prius PHV, which went on sale in 2016, was the world's first mass-produced system for using an VIPV module to charge a high-voltage drive battery and use it as driving energy. The Prius PHV is equipped with an VIPV panel with a rated output of 180 W, and it is calculated that the EV driving distance by generating electricity from the PV panel is up to 6.1 km/day in Japan. Following the Prius PHV, models such as the Karma Revero and Hyundai's Sonata HV, which can run on the power generated by onboard PV panels, have been released in the United

States and other countries. Additionally, in Japan, the bZ4X and Soltera, which are BEVs equipped with PV panels, have been started selling since 2022.

Recently, longer driving of more than 25 km/day by using solar energy has been demonstrated with Toyota Prius, Nissan EV test cars [6] by using high-efficiency VIPV modules such as III-V 3-junction solar cell modules with module efficiency of more than 30%, Sono Motors Sion [9] and Lighyear One [10] by using Si back contact solar cell modules with module efficiency of more than 20% for proof of concept. However, in order to realize longer driving of more than 30 km/day average, development of high-efficiency VIPV modules with module efficiency of more than 35% [12] is necessary as shown below.

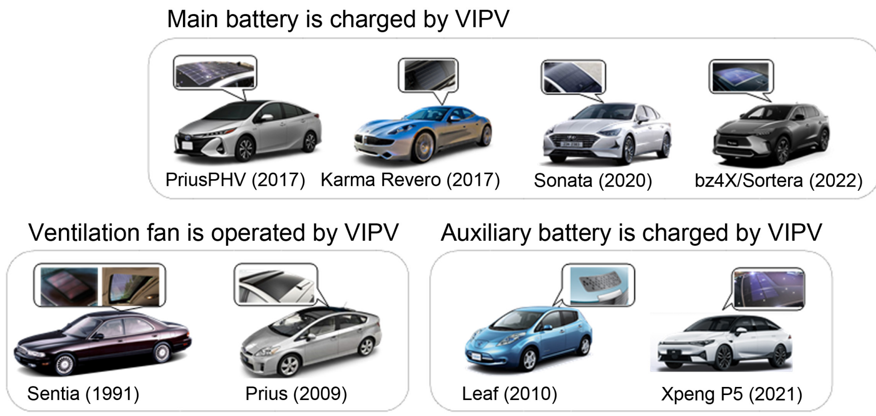

Figure 1. History of vehicle integrated photovoltaic systems.

3. Impact of High-Efficiency VIPV Module upon SEV

The effectiveness of the introduction of high-efficiency VIPV modules into EVs upon reduction in CO_2 emission was reported by the authors [13]. The VIPV-EV installed with the higher efficiency VIPV modules have a greater ability of reduction in CO_2 emission compared to EV. Annual CO_2 emission reduction of EV with electric mileage EM of 10 km/kWh in Japan is estimated to be 188 kg CO_2-eq/year (46% CO_2 reduction), 255 kg CO_2-eq/year (63% reduction) and 295 kg CO_2-eq/year (73% CO_2 reduction) for VIPV module efficiency of 20%, 30% and 40%, respectively. The experimental results of the Toyota demonstration car which showed that the annual CO_2 emission reduction by 62% [14] for a passenger car confirmed the validity of the calculated results [13]. From the view point of CO_2 emission reduction, the VIPV usage with the high conversion efficiency (>30%) is very effective for heavy vehicles which generally have low electric mileage such as vans, trucks and trailers [15].

Figure 2 shows calculated results for charging electricity cost saving of EV by usage of VIPV as a function of electric millage EM by using cumulative frequency [16] for daily mileage of Japanese passenger cars. The results show effectiveness of high-efficiency VIPV modules for charging electricity cost saving of EV.

Potential of daily driving distance DD of vehicles powered by various solar cell modules with various module efficiency η(%) was calculated by using Equation

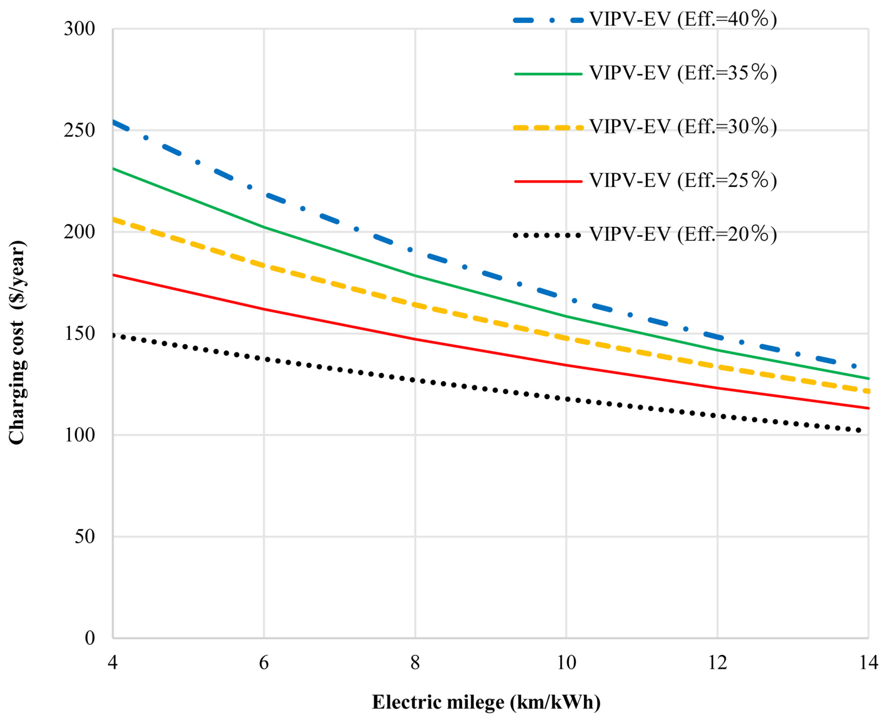

Figure 2. Calculated results for charging electricity cost saving of VIPV-EV as a function of electric millage EM by using cumulative frequency for daily mileage of Japanese passenger cars.

(1) and assuming the following conditions: 4 kWh/m^2/day for solar irradiation (SI), 3 m^2 for installation area (A) of solar cell modules, 0.739 [1] for system efficiency (SE) of PV systems including convertor and 9.35 km/kWh for electric mileage (EM) of vehicle (case of Toyota Prius demonstration car [6]).

$$\mathrm{DD[km/day]} = \mathrm{SI[kWh/m^2/day]} * \mathrm{SE} * \eta[\%] * \mathrm{A[m^2]} * \mathrm{EM[km/kWh]}, \quad (1)$$

Figure 3 shows estimated daily driving distance of vehicles powered by various solar cell modules of current module efficiency [17] in comparison with actual driving data for the PV driving range of the Toyota Prius demonstration car [6] and Sono Motor Sion [9]. Although our new world record efficiency 33.7% InGaP/GaAs/Si 3-junctuon solar cell module [18] has PV driving potential of about 28 km/day, further efficiency improvements of solar cell modules with an efficiency of more than 36% is very important to realize longer PV driving range of more than 30 km/day under solar irradiation of 4 kWh/m^2/day as shown in **Figure 3**.

4. Overview for VIPV and SEV

4.1. High-Efficiency and Low-Cost VIPV Modules

At first, properties of VIPV modules for passenger cars are overviewed. **Table 1** shows typical properties of VIPV modules for passenger car use in commercial phase and development phase by collecting date from references [2] [7] [9]-[11] [19]-[28].

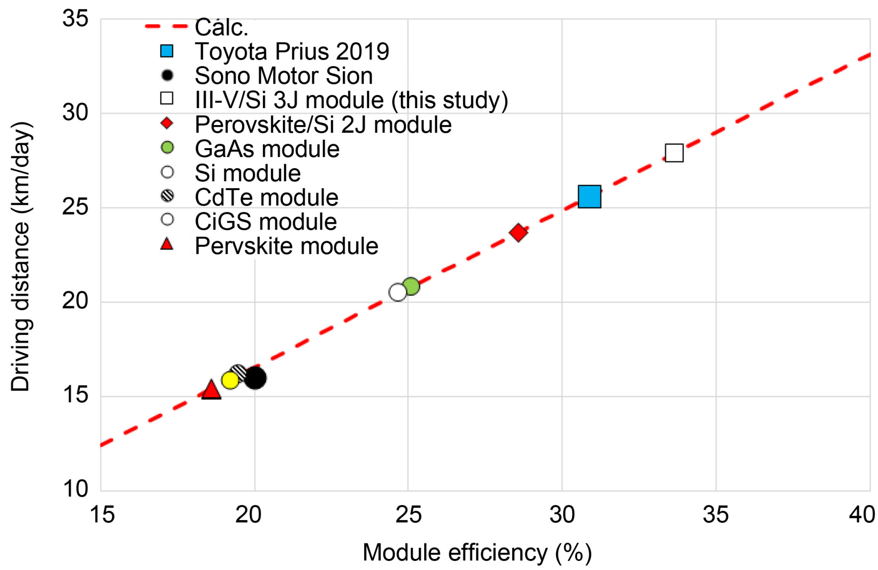

Figure 3. Estimated daily driving distance of vehicles powered by various solar cell modules of current module efficiency in comparison with actual driving data for the PV driving range of the Toyota Prius demonstration car and Sono Motor Sion.

In the beginning stage of developing VIPV-EV, low output power VIPV modules from 40 W to 120 W have been used for accessory use. Since 2017, VIPV modules with output power of more than 200 W have been used in order demonstrate partial contribution of vehicles and VIPV-EVs have shown driving of 5 - 6 km/day by solar energy. Recently, longer driving of more than 25 km/day by using solar energy has been demonstrated with Toyota Prius, Nissan EV test cars, Lighyear One and so forth by using high-efficiency VIPV modules such as III-V 3-J modules with module efficiency of more than 30% and Si-IBC modules with module efficiency of more than 20% for proof of concept. However, in order to realize longer driving of more than 30 km/day average, development of high-efficiency VIPV modules with module efficiency of more than 35% is necessary as shown in Figure 3. Table 1 also shows some approaches, such as III-V/Si 3-J and perovskite/Si 2-J tandem modules for this end.

4.2. Partial Shading, 3-Dimensional Curvature, and the Other Loss Aspects

PV used for automotive is partially shaded by the objects around the PV panel (or auto motive), and the output of PV is reduced owing to it. We demonstrated the partial shading effect on the output power and related loss by using Monte Carlo simulation [29] and evaluated the output of the PV panel mounted on the car roof under actual driving conditions [30]. Typically, VIPVs are 3-dimensionally curved because the shape of the car body is also curved and VIPV was architected along the car body. The curved shape causes the mismatching loss due to the self-shading effect and cosine loss.

We estimated the curved shape of the commercial car body [31]. We also

Table 1. Typical properties of VIPV modules for passenger car use in commercial phase and development phase.

Car company	Module company	Stage	PV area (m^2)	PV power (kW)	Solar cell type	Module efficiency (Solar cell efficiency)	PV price	Driving distance (km/day)	Announced Year
Audi A8, A6, A4		Commercial		0.04					1994
Volswagen Touareg Phaeton Passat		Commercial		0.04					1994
Mercedes E class Maybach		Commercial		0.04					1994
Toyota Prius	Kyocera	Commercial		0.056	Si mono	16.5%	$26.9/W		2009
Karma Fisker		Commercial		0.12	Si Mono			2.7	2011
Ford C-Max	SunPower	Proof of Concept	1.5	0.3	Si IBC	20%			2014
Toyota Prius IV	Panasonic	Commercial	0.9	0.18	Si HJ	20%	$8/W	6.1	2017
Sono Motors Sion		Proof of Concept	7.5	1.204	Si IBC	16% (24%)		~16	2018
Lightyear One		Proof of Concept	5	1.05	Si IBC			25.5	2019
Hanergy	Hanergy Solar	Proof of Concept	3.5 - 7.5	1 - 2	GaAs	(29%)		27 - 54.8	2019
Toyota Prius	Sharp	Proof of Concept		0.86	III-V 3-J	>30% (34%)		26.6	2019
Nissan EV	Sharp	Proof of Concept		1.15	III-V 3-J	>30% (34%)		~24.8	2019
Hyundai Sonata		Commercial	1.3	0.204	Si mono	15.7% (22.8%)	$5.4/W	5.4	2020
Toyota bZ4X	Kaneka	Commercial		0.225	Si HBC	(26.7%)	$8.5/W		2022
Toyota Prius PHEV	Kaneka	Commercial			Si HBC	(26.7%)			2023
	Maxeon	Development	1.7806		Si IBC	24.7			2023

Continued

Mia Sole	Development	1.0858	CIGS	18.6	2019
UtomLight	Development	0.0809	perovskite	18.6	2023
Kaneka	Development	0.0064	Perovskite/ Si 2-J	28.4	2023
Sharp Idemitsu	Development	0.0778	III-V/ CIGS 3-J	31.2	2023
Sharp Toyota TI	Development	0.0775	III-V/Si 3-J	33.7	2023

IBC: interdigitated back contact, HJ: hetero junction, HBC: heterojunction back contact.

measured effects of temperature rise of Si modules and usage of air-conditioners upon driving distance of SEV. Figure 4 summarizes effects of various power losses [32] upon driving distance of SEV according to test driving of Toyota Motor and Nissan Motor test cars. Usage of air-conditioners [32] shows higher power loss compared to partial shading [33] and temperature rise of solar cell modules [32]. In this analysis, self-shading loss due to 3-dimensional curvature was not considered.

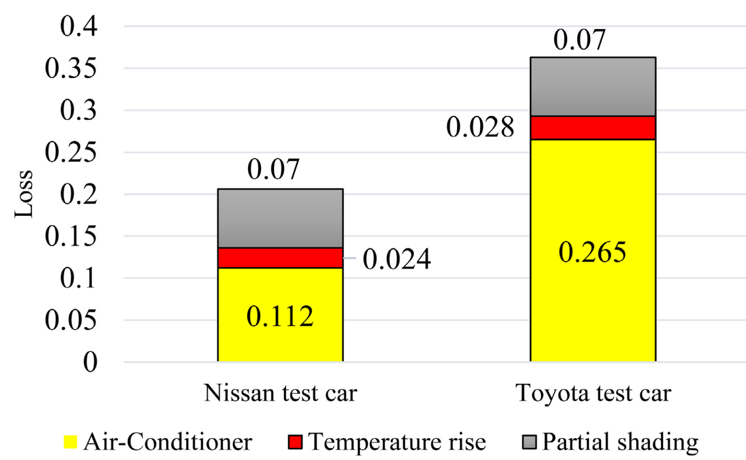

Figure 4. Analytical results of various power losses of SEV according to test driving by Toyota and Nissan test cars.

4.3. Colored PV Modules

There is another strong need to develop decorative PV panels that can offer desired colors for automotive applications. Since most PV panels exhibit a monotonous black or dark-blue appearance to maximize light absorption and minimize light reflection, Figure 5 shows that the 90% of incident sunlight is transmitted to the solar cell although it is covered by the colored layer. The study showed that the colors can be made on the PV panels with small output power reduction of less than 10% compared to the PV panels without the painting layer [34].

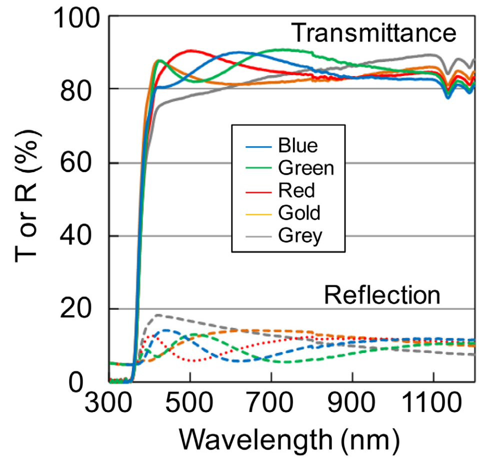

Figure 5. Measurement results of transmittance (T) and reflection (R) of the color layers fabricated on a transparent polycarbonate plate.

5. Reliability of VIPV

Reliabilities of the VIPV as the power sources and power devices are examined, tested, and qualified by both IEC and ISO standards. VIPV is one of the photovoltaic devices and also one of automobile components. The reference standards for design qualification for PV are the IEC61215 series, and the vehicle standards are the ISO16750 series. Both electrical device standards and automotive standards in AND (electrical device standards and automotive standards) conditions should be examined. VIPV differs from standard PV modules in several points, so the standard testing and rating methods cannot be applied, mainly by the shading impacts, curved surface, partial shading, dynamic shading, and environment (**Figure 6** [35]).

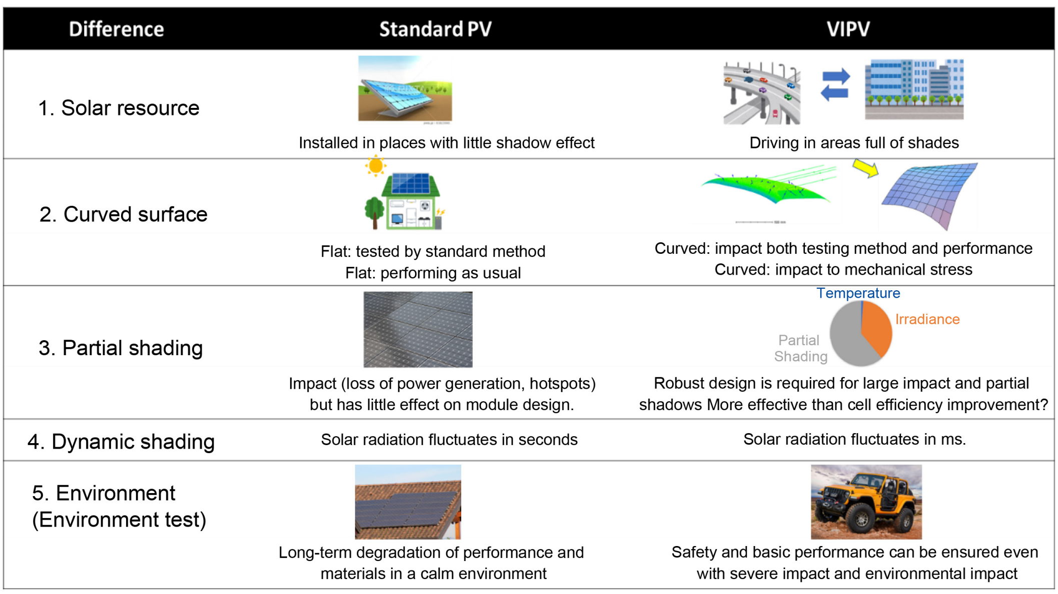

Figure 6. VIPV's performance, testing, and rating differences from standard PV technologies.

6. Expectations and Problems for VIPV and VIPV-Powered Vehicles

The expectations and problems for VIPV and Solar Electric Vehicles (SEV) were summarized as a to-do list in 2018 [36], which is still unchanged. High efficiency is important because it is directly linked to cruising distance. Since it is essential to follow a three-dimensional curved surface, that is, to cover the cell three-dimensionally, the development of such solar cells and PV modules is expected. A PV module (3D-curved PV module) with durability and vibration resistance is required to withstand the car environment [37].

Most formulas, equations, modeling, and measurement methods for photovoltaic devices are based on the assumption that photovoltaic devices are flat, static (with no movement), and illuminated uniform sunlight [35] [38]. It is a reasonable assumption for typical applications such as rooftop solar panels, but it cannot be applied to vehicle photovoltaic devices. For example, one of the essential equations that (Power output) = (Power conversion efficiency) × (Area of the device) × (Solar irradiance) is not true to the car applications in a physically and mathematically rigorous manner. Deviation of photovoltaic devices on vehicles is sometimes called "strange behaviors." We may need a general computation method for general curved surfaces and nonuniform shading (aperture) environments. Such computation requires a shading (aperture) matrix instead of shading ratio or angle (scalar), to a tensor form (4-Tensor) for the angular response to the incident light instead of the Lambertian curve, differential geometry description using vector expression of a unit element, instead of cosine loss by angles of the PV panel (**Table 2**). Even the coordinate system may shift to a local coordinate system with 3D rotation instead of absolute ground coordinates.

Table 2. Comparison table of the differences between vehicle applications and typical PV devices.

Key issues	Typical PV Devices	Vehicle Applications
Basic math	Arithmetic with trigonometric functions	Vector computations
Coordinate system	Absolute ground coordinates	Local coordinates with 3D rotation
Sky model	Uniform hemisphere sky (Shading ratio - Scalar)	Nonuniform shading on hemisphere sky (Shading matrix - Matrix)
Partial and dynamic shading	Time integration with weighting	Statistical model on probabilities and expected values
Shape of PV devices (cells and modules)	Flat surface	Curved surface (undevelopable curved surface) based on differential geometry.
Stress calculation	Bending load to a thin plate	Buckling by 3D bending due to coverage on an undevelopable curved surface (Differential geometry and continuum dynamics)
Ray orientation	Cosine	The inner product between the normal vector of the surface element and rays
Angular response	Lambertian	4-Tensor

7. Perspective for VIPV and SEV

Shortly, when EVs become mainstream, VIPV is expected to solve the grid burden problems and lack of charging facilities. Of course, it also contributes to reducing CO_2 emissions. Above all, we hope you can enjoy freedom in many senses: freedom from refueling, battery charging, and carbon-free.

One of the killer applications of the SEV is the energy source in a disaster zone [35]. SEVs save energy through vehicle-integrated photovoltaics (VIPV) and make it possible to donate excess energy voluntarily, thus maintaining facility resilience.

Other promising applications are for heavy-duty vehicles (HDVs). The PV will be valid for saving the fuels of HDV by taking over the energy consumption by alternators and compressors [15] [39] [40]. However, the amount of fuel saving is not precise, varying by the driving modes, driving zones, types of HDVs, and driving habits. An accurate and precise advantage is essential for the logistic companies' decision to invest PV on their HDVs. An R&D project is wanted to investigate the energy yield of PV on the HDVs and clarify the fuel-saving amount in various situations.

8. Summary

This paper presented a topical review for the vehicle-integrated photovoltaics (VIPV). In this paper, impacts of high-efficiency solar cell modules on increases in vehicle driving distance, reducing CO_2 emission, and charging cost saving of EV powered by VIPV modules were shown. This paper overviewed development of high-efficiency VIPV modules and discussed about reliability, partial shading 3-dimensional curvature and color variations of VIPV modules. Analytical results for some power losses of solar-powered electric vehicles (SEV) by using test driving data by Toyota Motor and Nissan Motor test cars installed with high-efficiency III-V compound 3-junction solar cell modules with a module efficiency of more than 30% were shown in this paper. This paper also presented prospects for VIPV modules.

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Data Availability Statement

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

Authors' Contribution

We expect that all authors will have reviewed, discussed, and agreed to their individual contributions ahead of this time. Contributions will be published before the references section, and they should accurately reflect contributions to the work. The following statements should be used Conceptualization, M.Y. and T.M., Methodology, M.Y. and T.M., Validation, Y.O., K.A. N.K. and M.Y., Formal Analysis, Y.O., K.A. N.K. and M.Y., Module installation, Y.O., Investigation, all, Data Curation, all, Writing Original Draft Preparation, all, Writing Review & Editing, M.Y., Visualization, T.M., Supervision, Y.O. and M.Y.; Project Administration, Y.O. and K.N.; Funding Acquisition, Y.O. and K.N.

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Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Masuda, T., Araki, K., Okumura, K., Urabe, S., Kudo, Y., Kimura, K., *et al*. (2017) Static Concentrator Photovoltaics for Automotive Applications. *Solar Energy*, **146**, 523-531. https://doi.org/10.1016/j.solener.2017.03.028

[2] Miyoshi, T. (2017) Solar Charging System for Prius PHV. *Journal of the Japan Society of Applied Electromagnetics and Mechanics*, **25**, 379-382. https://doi.org/10.14243/jsaem.25.379

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

[4] Sierra Rodriguez, A., de Santana, T., MacGill, I., Ekins-Daukes, N.J. and Reinders, A. (2019) A Feasibility Study of Solar PV-Powered Electric Cars Using an Interdisciplinary Modeling Approach for the Electricity Balance, CO_2 Emissions, and Economic Aspects: The Cases of the Netherlands, Norway, Brazil, and Australia. *Progress in Photovoltaics*: *Research and Applications*, **28**, 517-532. https://doi.org/10.1002/pip.3202

[5] Yamaguchi, M., Masuda, T., Araki, K., Sato, D., Lee, K., Kojima, N., *et al*. (2020) Role of PV-Powered Vehicles in Low-Carbon Society and Some Approaches of High-Efficiency Solar Cell Modules for Cars. *Energy and Power Engineering*, **12**, 375-395. https://doi.org/10.4236/epe.2020.126023

[6] Yamaguchi, M., Masuda, T., Araki, K., Sato, D., Lee, K., Kojima, N., *et al*. (2020) Development of High-Efficiency and Low-Cost Solar Cells for PV-Powered Vehicles Application. *Progress in Photovoltaics*: *Research and Applications*, **29**, 684-693. https://doi.org/10.1002/pip.3343

[7] Commault, B., Duigou, T., Maneval, V., Gaume, J., Chabuel, F. and Voroshazi, E. (2021) Overview and Perspectives for Vehicle-Integrated Photovoltaics. *Applied Sciences*, **11**, Article 11598. https://doi.org/10.3390/app112411598

[8] Thiel, C., Gracia Amillo, A., Tansini, A., Tsakalidis, A., Fontaras, G., Dunlop, E., *et al*. (2022) Impact of Climatic Conditions on Prospects for Integrated Photovoltaics

in Electric Vehicles. *Renewable and Sustainable Energy Reviews*, **158**, Article 112109. https://doi.org/10.1016/j.rser.2022.112109

[9] Sono Motors. https://sonomotors.com/en/sion/

[10] Lightyear. https://lightyear.one/lightyear-one

[11] IEA/PVPS Task 17 (2021) State-of-the-Art and Expected Benefits of PV-Powered Vehicles. Report IEA-PVPS T17-01.

[12] Yamaguchi, M., Masuda, T., Araki, K., Ota, Y. and Nishioka, K. (2022) Impact and Recent Approaches of High-Efficiency Solar Cell Modules for PV-Powered Vehicles. *Japanese Journal of Applied Physics*, **61**, SC0802. https://doi.org/10.35848/1347-4065/ac461b

[13] Yamaguchi, M., Masuda, T., Nakado, T., Yamada, K., Okumura, K., Satou, A., *et al.* (2023) Analysis for Expansion of Driving Distance and CO_2 Emission Reduction of Photovoltaic-Powered Vehicles. *IEEE Journal of Photovoltaics*, **13**, 343-348. https://doi.org/10.1109/jphotov.2023.3242125

[14] Masuda, T., Nakado, T., Yamaguchi, M., Takamoto, T., Nishioka, K. and Yamada, K. (2022) Public Road Tests of Toyota Prius Equipped with High Efficiency PV Module with Output Power of 860W. 2022 *IEEE 49th Photovoltaics Specialists Conference* (*PVSC*), Philadelphia, 5-10 June 2022, 467. https://doi.org/10.1109/pvsc48317.2022.9938532

[15] Kutter, C., Alanis, L.E., Neuhaus, D.H. and Heinrich, M. (2021) Yield Potential of Vehicle Integrated Photovoltaics on Commercial Trucks and Vans. 38*th European PV Solar Energy Conference and Exhibition* 2021, Online, 6-10 September 2021, 1412-1420. https://doi.org/10.4229/EUPVSEC20212021-6DO.8.2

[16] Yamaguchi, M., Nakamura, K., Ozaki, R., Kojima, N., Ohshita, Y., Masuda, T., *et al.* (2022) Analysis for the Potential of High-Efficiency and Low-Cost Vehicle-Integrated Photovoltaics. *Solar RRL*, **7**, Article 2200556. https://doi.org/10.1002/solr.202200556

[17] Green, M.A., Dunlop, E.D., Yoshita, M., Kopidakis, N., Bothe, K., Siefer, G., *et al.* (2023) Solar Cell Efficiency Tables (Version 63). *Progress in Photovoltaics: Research and Applications*, **32**, 3-13. https://doi.org/10.1002/pip.3750

[18] Yamaguchi, M., Takamoto, T., Juso, H., Nakamura, K., Ozaki, R., Masuda, T., *et al.* (2024) Approaches for III-V/Si Tandem Solar Cells and Comparative Studies on Si Tandem Solar Cells. *Progress in Photovoltaics: Research and Applications*. https://doi.org/10.1002/pip.3780

[19] Nanosolar. http://www.nanosolar.com/

[20] Retractable Car Cover Claimed to Gain Miles of EV Range Each Day. https://www.autoklimaanlage.info/fileadmin/user_upload/Tagung_2013/PRO_KLIMA_Wecker_Potentials_of_Solar_Systems_in_Vehicles_for_Air_Conditioning_2013-12-04.pdf

[21] Car Watch. https://car.watcg.impress.co.jp/docs/new/169516.html

[22] Ford C-Max Solar Energi: La Première Vraie Voiture Solaire? Automobile. https://www.lepoint.fr/automobile/innovations/ford-c-max-solar-energi-la-premiere-vraie-voiture-solaire-03-01-2014-1776499_652.php

[23] Hanergy Solar R. https://www.allcarindex.com/concept/china/hanergy/solar-r/

[24] SunWare Series-20. https://en.sunware.solar/static/modules_pdf/DB_Module_20_2022_US.pdf

[25] 2020 Hyundai Sonata Hybrid: What to Expect from Its Mpg-Boosting Solar Roof. https://www.greencarreports.com/news/1127957_2020-hyundai-sonata-hybrid-

what-to-expect-from-its-mpg-boosting-solar-roof

[26] Toyota. https://global.toyota/newsroom/toyota/36254708.html

[27] Kaneka. https://www.kaneka.co.jp/topics/news/2023/nr230328.html

[28] Oxford PV Sets 28.6% Efficiency Record for Full-Size Tandem Cell. https://www.pv-magazine.com/

[29] Araki, K., Lee, K., Masuda, T., Hayakawa, Y., Yamada, N., Ota, Y., *et al*. (2019) Rough and Straightforward Estimation of the Mismatching Loss by Partial Shading of the PV Modules Installed on an Urban Area or Car-Roof. 2019 *IEEE* 46*th Photovoltaic Specialists Conference* (*PVSC*), Chicago, 16-21 June 2019, 1218-1225. https://doi.org/10.1109/pvsc40753.2019.8981199

[30] Ota, Y., Araki, K., Nagaoka, A. and Nishioka, K. (2021) Evaluating the Output of a Car-Mounted Photovoltaic Module under Driving Conditions. *IEEE Journal of Photovoltaics*, **11**, 1299-1304. https://doi.org/10.1109/jphotov.2021.3087748

[31] Ota, Y., Araki, K., Nagaoka, A. and Nishioka, K. (2021) Curve Correction of Vehicle-integrated Photovoltaics Using Statistics on Commercial Car Bodies. *Progress in Photovoltaics: Research and Applications*, **30**, 152-163. https://doi.org/10.1002/pip.3473

[32] Yamaguchi, M., Nakamura, K., Ozaki, R., Kojima, N., Ohshita, Y., Masuda, T., *et al*. (2023) Analysis of Climate Conditions Upon Driving Distance of Vehicle Integrated Photovoltaics-Powered Vehicles. *Energy Technology*, **12**, Article 2300692. https://doi.org/10.1002/ente.202300692

[33] Hirota, T., Kim, Y., Kobayashi, K., Kamiya, Y., Maeshima, S. and Komoto, K. (2022) Feasibility Study of Onboard PV for Passenger Vehicle Application (Second Report)—Influence of Vehicle Irradiation on Energy Balance of PV Generation and EV Energy Consumption. *Transactions of Society of Automotive Engineers of Japan*, **53**, 784-789. https://doi.org/10.11351/jsaeronbun.53.784

[34] Masuda, T., Hirai, S., Inoue, M., Chantana, J., Kudo, Y. and Minemoto, T. (2018) Colorful, Flexible, and Lightweight Cu(In, Ga)Se_2 Solar Cell by Lift-Off Process with Automotive Painting. *IEEE Journal of Photovoltaics*, **8**, 1326-1330. https://doi.org/10.1109/jphotov.2018.2859743

[35] Araki, K., Ota, Y., Maeda, A., Kumano, M. and Nishioka, K. (2023) Solar Electric Vehicles as Energy Sources in Disaster Zones: Physical and Social Factors. *Energies*, **16**, Article 3580. https://doi.org/10.3390/en16083580

[36] Araki, K., Ji, L., Kelly, G. and Yamaguchi, M. (2018) To Do List for Research and Development and International Standardization to Achieve the Goal of Running a Majority of Electric Vehicles on Solar Energy. *Coatings*, **8**, Article 251. https://doi.org/10.3390/coatings8070251

[37] Yamada, N. (2022) Development of 3D Curved Photovoltaic Modules. *JSAP Review*, **2022**, Article ID: 220402. https://doi.org/10.11470/jsaprev.220402

[38] Araki, K., Ota, Y., Nagaoka, A. and Nishioka, K. (2023) 3D Solar Irradiance Model for Non-Uniform Shading Environments Using Shading (Aperture) Matrix Enhanced by Local Coordinate System. *Energies*, **16**, Article 4414. https://doi.org/10.3390/en16114414

[39] Mallon, K., Assadian, F. and Fu, B. (2017) Analysis of On-Board Photovoltaics for a Battery Electric Bus and Their Impact on Battery Lifespan. *Energies*, **10**, Article 943. https://doi.org/10.3390/en10070943

[40] Sierra, A. and Reinders, A. (2020) Designing Innovative Solutions for Solar-Powered Electric Mobility Applications. *Progress in Photovoltaics: Research and Applications*, **29**, 802-818. https://doi.org/10.1002/pip.3385