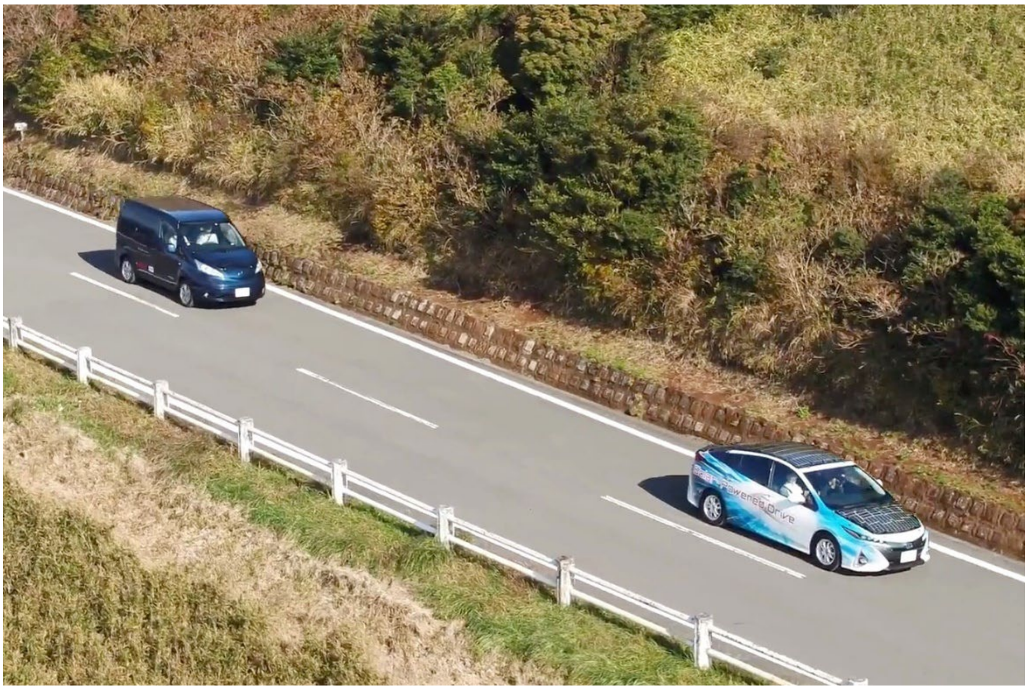
PV-Powered Vehicle Strategy Committee

Interim Report (3)

- Demonstration Driving of PV-Powered Vehicles, and Research for Practical Realisation -



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New Energy and Industrial Technology Development Organization

Interim Report of PV-Powered Vehicle Strategy Committee (3): Table of Contents

Introduction

The transport sector will have to play a significant role in achieving carbon neutrality by 2050, and measures by the automotive sector will be of great importance. In order to reduce greenhouse gas emissions from cars, initiatives aiming at a rapid rollout of the electrification of vehicles have begun in countries across the world. However, unless clean power derived from renewable energy sources can be supplied, such vehicles will have a limited effect in reducing greenhouse gas emissions.

At present, emissions of greenhouse gases are falling in the power generation sector due to the accelerated introduction of renewable energy, such as solar (hereinafter, photovoltaic or "PV") and wind. In the transport sector however, which relies on fossil fuel for most of its energy needs, revolutionary technological development will be required to outperform current greenhouse gas reduction targets.

In response to this situation, NEDO established the PV-Powered Vehicle Strategy Committee (secretariat: Mizuho Research & Technologies, Ltd.). This committee investigated the potential benefits and outstanding issues for installing high-efficiency PV on automobiles and reported in January 2018 on its potential for reducing the CO2 emissions in the transport sector[i]. This report also indicated that solar irradiation and generated power differ between PV on vehicle and PV installed on the roof or rooftop of a building, and stressed the need for quantitative analysis into this difference. In keeping with this recommendation, the solar irradiation of vehicles was measured at two locations in Japan (in Hokkaido and Miyazaki Prefectures), and the results of these measurements were reported in April 2019[ii].

In parallel with these activities, in 2019, NEDO launched a demonstration driving of PV-powered vehicles containing innovative, high-performance PV (ultra-high-efficiency PV cells) that were developed through a NEDO project[iii,iv]. This trial has produced various results, and the project continues to identify challenges in the commercialisation of this technology and to deliberate regarding how these challenges can be surmounted. Various technical development is also being performed to create the foundation for the full-fledged realisation of PV-powered vehicles.

This PV-Powered Vehicle Strategy Committee report provides an overview of trends in PV-powered vehicles, the primary results of the demonstration driving of PV-powered vehicles that use ultra-high-efficiency PV cells with rated outputs of 1 kW or more, and a summary of the state of technology initiatives that will serve as the foundation of the full-fledged realisation of these vehicles in the future.

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[i] NEDO, PV-Powered Vehicle Strategy Committee Interim Report, January 2018 (https://www.nedo.go.jp/content/100885778.pdf)

[ii] NEDO, PV-Powered Vehicle Strategy Committee Interim Report (2) - Preliminary Study on Solar Irradiation of PV-Powered Vehicles-, January 2018 (https://www.nedo.go.jp/content/100896335.pdf)

[iii] NEDO, Press Release "NEDO, Sharp, and Toyota to Begin Public Road Trials of Electrified Vehicles Equipped with High-efficiency Solar Batteries", 4 July 2019 (https://www.nedo.go.jp/english/news/AA5en_100408.html)

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Chapter 1: Trends in PV-Powered Vehicles

In recent years, countries around the world have been intensifying their efforts to reduce CO_2 emissions. The automobile industry, as well, is dedicating itself to decarbonisation initiatives. At the start of the 21st century, the number of global annual vehicle production was around 60 million, but by the late 2010s it had risen to over 90 million. The number of vehicles owned worldwide surpassed 1.4 billion in 2018. As developing nations advance economically, their annual production and ownership numbers of vehicles are expected to grow[1].

To reduce CO_2 emissions from automobiles, companies are accelerating their efforts to develop environmentally-friendly (electric) vehicles, such as hybrid vehicles (HEVs), plug-in hybrid vehicles (PHEVs), fuel cell electric vehicles (FCEVs), and battery electric vehicles (BEVs).

On the other hand, looking outside the transport sector, advances are being made in the use of renewable energy such as solar power as a promising approach for cutting CO_2 emissions in the residential and electricity sectors. Renewable energy is now the most inexpensive power source in many nations, and its importance continues to rise.

When a PV system is installed on an electric vehicle (including a plug-in hybrid vehicle) and the generated power is used to drive the vehicle, there are expected benefits such as a reduction in CO_2 emissions compared to when a vehicle is externally charged using grid, and a reduction in the frequency of external charging operations[2]. This aligns with the global trends of promoting the vehicle electrification. Although the output of PV is not large, PV-powered vehicles are gradually advancing toward commercial release. Technological development, such as the improvement of PV performance, is also being carried out to assist with the full-fledged practical application of PV-powered vehicles.

An overview of PV-powered vehicle commercialisation trends and NEDO efforts to develop and realise PV-powered vehicles are presented below.

1.1 PV-powered Vehicle Commercialisation Trends

1.1.1 Installation of PV on Passenger Vehicles

The installation of PV on automobiles was originally proposed in the 1980s and began in early 1990s. The Mazda Sentia, launched in 1991, and the Audi A6, launched in 1993, had PV built onto their sunroofs. The rated output of the PV was several tens of watts, and used to power fans for ventilating the interior. The third generation Prius, launched in 2009, also had a similar PV system installed. The Nissan Leaf, released in the following year, made it possible to charge the auxiliary (12V) battery with installed PV. However, automobiles run on solar power from installed PV were not sold until recently. In January 2014, Ford announced a concept car that used PV as its energy source. Various car manufacturers then began to investigate the potential of PV as a power source for electric vehicles.

Table 1.1-1 shows examples of passenger cars that currently on market and those planned for future release, equipped with PV systems for power for driving.

Table 1.1-1 Examples of PV-powered passenger cars

Name and manufacturer	Category	PV output (W)	Battery capacity (kWh)	Vehicle weight (kg)	Kilometres per kWh	Cruising Range （km）	Release year (including plan*2)
Prius[3] (Toyota)	PHEV	180 W[4]	8.8	1,510	—	—	2017
Karma Revero[5] (Karma)	PHEV	200 W	28	2,688	—	—	2017
Sonata[6] (Hyundai)	HEV	205 W	—	1,584 ～1,595	—	—	2020
bz4x[7] (Toyota)	BEV	225 W	71.4	2,195 ～2,285	6.8~8.8	540~559	2022
IONIQ 5[8] (Hyundai)	BEV	205 W	58～ 72.6	1,870 ～2,100	7.0~7.6	498~618	2022
Sion[9] (Sono Motors)	BEV	1,200 W	54	1,730	6.3	305	2022
Lightyear 0[10] (Lightyear)	BEV	1,075 W (5 m^2)	60	1,575	9.3~10.4*1	560~625	2022
Fisker OCEAN[11] (Fisker)	BEV	—	100	1,815	4.0~5.6*1	400~560	2022
Cybertruck[12] (Tesla)	BEV	—	—	—	—	—	2023
Vision EQXX[13] (Mercedes)	BEV	—	100	1,755	11.5	1,000~	—

*1: Calculated as ‘Driving range (km) / Battery capacity (kWh)’, *2: as of September 2022

The world's first mass-produced automobile to use vehicle-mounted PV to charge high voltage batteries for propulsion was the Prius PHEV launched in 2017. The Prius PHEV had an optional crystalline silicon solar cells with an output of 180 W. Although the PV alone was not enough to drive the vehicle, the expected driving range under power generated using the PV per day was calculated as being up to 6.1 km/day. This was followed by the launches of models using power generated by onboard PV, such as the 2017 Karma Revero (rated output 200 W) and the 2020 Hyundai Sonata HEV. The Sonata HEV's chassis roof had a 205 W LG-made PV module (only available for the top end model) made up of 46 cells, with a curved glass surface. Power generated by the PV was used to charge the direct-drive battery, a very different system than the Prius PHEV, which used PV to charge the sub-battery for buffering.

Looking at the trends from 2022 onward, PV module capacities have grown larger, and the range of mass-market product variations has grown more diverse.

In 2022, Toyota Motor Corporation began selling the bz4x, a SUV-type BEV. One of the vehicle's options are a charging system that uses solar power (solar power system). The bz4x has both a drive battery and an auxiliary battery. While parked, the solar charging system charges the drive battery, and while driving, it supplements the power consumption of the auxiliary battery system, helping provide the vehicle with a longer driving distance[7].

Hyundai is planning the launch of the IONIQ 5 (BEV), which will have the same model of PV module as the Sonata[6]. Hyundai has also worked with Kia Motors to develop vehicle-mounted PV. They have announced plans to develop "Silicone-type Solar Roof," which installs crystalline silicon solar cells on the roof, as the 1st generation, "Translucent Solar Roof," which installs translucent PV on the roof, as the 2nd generation, and the "Solar Lid," which is installed on bonnets and the entire roof surface, as 3rd generation[14].

In Europe, Sono Motors plans to launch the Sion, and Lightyear will launch the Lightyear 0*. Both will be BEVs. In the case of the Sono Motors Sion, PV will be installed not only on the top of the chassis, but also on its sides and rear, for a PV output of 1.2 kW (1,200 W) (Fig. 1.1-1)[9]. The PV cover will not use glass, as in previous vehicles, but instead abrasion-resistant, lightweight polymer. The Lightyear 0, on the other hand, will have PV covering from the bonnet to the entire upper chassis, achieving a capacity of 1 kW (Fig. 1.1-2)[10].

Plans have also been announced for the launch of PV-powered vehicles in 2023 and beyond, and Tesla and Mercedes are engaged in active development.

Fig. 1.1-1 Example of a PV-powered Vehicle
(1) Sono Motors - Sion[9]

Fig. 1.1-2 Example of a PV-powered Vehicle
(2) Lightyear – Lightyear 0[10]

1.1.2 PV-Powered Vehicles Other Than Passenger Vehicles

Efforts to equip vehicles with PV systems are extending beyond just passenger vehicles.

(1) Installation of PV systems in trucks and trailers

Trailar Ltd, a spin-off of logistics giant DHL, has developed and commercially launched a system with thin film PV on the roofs of trailers to reduce vehicle fuel consumption. This system can be used in a wide range of applications, such as trucks, trailers, buses, and refuse collection trucks. One of the advantages of thin film PV is its slimness, so vehicles do not need to be re-registered after the modules are installed. In addition to DHL, this system is currently being used by Loyal Mail and Go-Ahead Group and by ALBA Group[15].

IM Efficiency is also carrying out initiatives to install PV on the roofs of box-type trailers[16]. Currently, the PV being used is crystalline Si module, and in addition to installation on trailer roofs, the company is also studying the potential and effectiveness of installation on the sides of trailers.

Efforts to use PV on trucks have also begun in Japan. Nagasaki Logistics Co., Ltd. has provided demonstration trucks for the trials which have PV modules on top of 10 tonne refrigerator van trailers. Thin film PV has been installed, and it is reported that fuel consumption has been reduced by over 5%[17].

*In 2023, both companies cancelled manufacturing such passenger cars.

Since December 2020, PLM Fleet, a refrigerated trailer leasing and rental company jointly funded by Mizuho Leasing Company, Limited and Marubeni Corporation, has been supplying refrigerator and freezer unit-equipped trailers designed and manufactured by Advanced Energy Machines with installed PV modules and battery storage systems[18]. The power generated by the PV modules is supplied to a battery storage system installed beneath the trailer and is used exclusively for the refrigerated trailer. These activities were prompted by moves in the U.S., especially in California, toward achieving zero emissions, and the increased attention being turned to the hybridisation and electrification of trailers using diesel engines and other similar vehicles.

Research institutes are also carrying out initiatives related to the electrification of trucks. Fraunhofer ISE is performing trials of electric cargo transport trucks with PV modules[19]. The electric cargo transport trucks used in the tests have a 3.5 kW PV module and an 800 V high voltage battery, reputedly capable of supplying 5 to 10% of the energy used by the trucks[20].

(2) Installation of PV modules in compact cars

In addition to general passenger vehicles and truck trailers, PV is increasingly being installed in compact cars.

Aptera Motors is developing the Aptera, a three-wheeled BEV that will be able to operate using PV alone. It plans to begin full-scale production in 2023. Thanks to a design focused on aerodynamics and reducing rolling resistance, the model with a 100 kWh battery capacity will have a cruising range of 1,000 km[21]. Furthermore, as it is a three-wheeled BEV, it will be classified as a motorcycle, not an automobile, making it comparatively easier to meet safety standards[22].

Squadmobility plans to sell a lightweight four-wheeled vehicle with PV mounted on its chassis roof in 2022. Squadmobility's vehicle will also not be categorized as an automobile, but instead will be in the light quadricycle (L6e) category. It will have a maximum speed of roughly 45 km/h, and is drawing interest as one type of next-generation mobility[23].

1.2 NEDO Initiatives Aimed at the Realisation of PV-powered Vehicles

Passenger vehicles with PV rated output of roughly 200 W are being commercially launched, and the variety of models available is increasing, albeit slowly. PV-powered vehicles use photovoltaic power for their drive energy, reducing the frequency of external charging. When the CO_2 emissions associated with charging are high, this can contribute to CO_2 emissions reduction. Hopes are high that these benefits will become greater as the performance of PV, that is, the output of the PV installed on vehicles, rises. From this perspective, initiatives have been carried out which seek to install highly efficient PV over a larger surface area to increase the amount of solar power output and, under certain conditions and driving environments, enabling driving vehicles using solar power alone.

The activities of European venture companies such as Sono Motors and Lightyear (mentioned earlier), are examples of such initiative. While in Japan, as well, NEDO collaborated with Toyota Motor Corporation, Nissan Motor Co., Ltd., and Sharp Corporation, in the development of PV-powered vehicles in fiscal years 2019 and 2020 (Figs. 1.2-1 and 1.2-2). These demonstration vehicles are equipped with ultra-high-efficiency PV cells with a power generation efficiency of over 30%, and public road trials are still being carried out. In addition to data concerning the power generation performance of PV themselves, a variety of other data is also being collected in preparation for the full-fledged use of PV as a vehicle drive power source. Chapter 2 of this report provides a partial overview of the findings gained so far.

Fig. 1.2-1 PV-powered demonstration vehicle (1) Prius PHEV (Toyota Motor Corporation)[24]

Fig. 1.2-2 PV-powered demonstration vehicle (2) eNV200 (Nissan Motor Co., Ltd.)[25]

Alongside this trial of PV-powered vehicle, in fiscal year 2020, NEDO began to conduct the research and development aimed at the commercialisation of low-cost, high-performance PV intended for use in transport such as automobiles (Table 1.2-1). This research and development project is being led by PV manufacturers and conducted together with participating companies, research organizations, and universities. Furthermore, to accelerate the development of these technologies, research and development, market trend studies, and market trend analyses are being conducted both inside Japan and overseas. Trend studies are also being conducted in order to deliberate regarding the future directions. Chapter 3 of this report provides a partial overview of the results obtained so far through R&D and trend studies.

Table 1.2-1 NEDO's PV R&D projects regarding transportation-related applications[26]

Research and development of solar cells for transportation-related applications / Development of ultra-high-efficiency module technology	Develop high efficiency technologies, cost reduction technologies new cell and module structures, and modularisation technologies for mounting on vehicles, etc. of PV (such as III-V compound multi-junction PV cells, III-V/Si, III-V/CIS, and other tandem PV) that do not require tracking to match the sun's irradiation direction, and will have a module efficiency of over 35% at AM1.5 spectrum.
Research and development of solar cells for transportation-related applications / Development of next-generation module technology	Develop low-cost crystalline silicon-based modules that have a conversion efficiency of over 30% and the ability to conform to curved surface. This includes, for example, the development of tandem technologies for perovskite/Si, etc., and 3D curved surface module technologies.
Trend survey of solar cells for transportation-related applications	Participate in activities such as IEA PVPS Task17 (PV and Transport), investigate and analyse R&D trends and market movements, both in Japan and overseas, related to PV for use in transport such as electric vehicles, deliberate regarding future directions, and accelerate research and development in the transport sector.

The IEA PVPS Task17: PV and Transport project conducted as part of this trend study, in which NEDO is participating, is an international cooperative project under the IEA. Japan is leading the project as 'Task manager' (chair). In 2021, the analyses were conducted on trends of PV-powered vehicle and the expected benefits of their commercialisation. A technical report[27] was produced and has been made publicly available on the IEA PVPS website, so please review it as needed.

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[11] Fisker Inc., “Fisker Ocean” Homepage (https://www.fiskerinc.com/ocean) (Confirmed, 4 October 2022)

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Chapter 2: Demonstration Driving of PV-Powered Vehicles: Findings and Future Challenges

CO_2 emissions from the transport sector account for roughly 21% of global emissions, of which, roughly 39% are reported to come from passenger vehicles[1]. Companies around the world are accelerating their development of environmentally friendly (electric) vehicles to reduce CO_2 emissions. Plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs), which equipped with high-capacity batteries, are good matches for renewable energy. PV panels are the form of plates, so they are especially well-suited for mounting on vehicles. However, although a great deal of research has been carried out on the application of solar energy to the transport sector (using PV power generated onboard), mass production is still in the developing stage, with only a handful of electric vehicles starting to utilize it.

In this context, demonstration projects (which consist of developing demonstration vehicles and performing trials by driving the vehicles on public roads) for installing PV on electric passenger vehicles and use them as a drive power source (supplying the vehicle's drive power with solar power) are being carried out through collaboration between NEDO-led technology development projects and automobile manufacturers (Toyota Motor Corporation and Nissan Motor Co. Ltd.).

Herein, an overview of the main findings from PV-powered PHEV and BEV demonstration driving, along with the challenges identified will be provided.

2.1 Installation of PV Systems on Plug-in Hybrid Vehicles: Reducing CO_2 Emissions and Charging Frequency

2.1.1 Objectives of Demonstration and Vehicle Specifications

Toyota Motor Corporation, together with NEDO and Sharp Corporation, manufactured a demonstration vehicle with a rated power generation output of approximately 860 W by installing III-V compound triple-junction PV cells with a conversion efficiency of over 30% on the roof, bonnet, and rear hatch door of a commercially available Prius PHEV (with a battery capacity of 8.8 kWh) (Fig. 2.1-1). The demonstration vehicle was used in public road driving in Aichi Prefecture, starting in July 2019, to demonstrate the possible driving distance and the effect of reduced charging frequency of using on board PV-generated power.

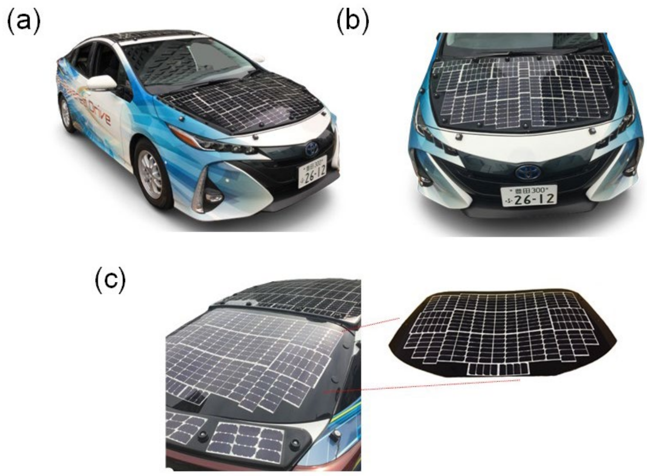


Fig. 2.1-1 PV-powered PHEV demonstration model

2.1.2 The Effect in Reducing CO_2 Emissions (Simulation)

Hopes are high that using PV-generated-power to run the car (replacing the charging power required for driving with PV) will reduce CO_2 emissions. Before performing demonstration driving, a simulation was conducted for the expected CO_2 emissions reduction effects that could be achieved by using PV-powered passenger vehicles. Here, some of the results of this simulation (Fig. 2.1-2) will be explained.

Annual driving data and local weather data for the areas where cars were driven were collected from 5,000 drivers across Japan, and a simulation was conducted of how much distances could have been driven by using PV. This analysis tried to approximate actual conditions to the greatest degree possible, and assumed that vehicles that were parked where there was no sunlight, such as vehicles regularly parked in indoor parking spaces, would have zero mileage from PV.

The following assumptions were used in calculations: the rated output of PV-powered passenger vehicles was assumed to be 1 kW (5 m^2 for a module with a conversion efficiency of 20%), the charging efficiency from PV power generation to the battery was assumed to be 74%, the electric charging system (ECS) power consumption was assumed to be 120 Wh/day, the vehicle driving power consumption was assumed to be 10 km/kWh, and the battery capacity was assumed to be 4 kWh (assuming the vehicle is a PHEV)[2].

The simulation found that roughly 30% of the total cruising distance could be achieved using solar energy alone (reducing CO_2 emissions). CO_2 emissions from passenger vehicles account for roughly 10% of total global CO_2 emissions, so based on these findings, the use of PV-powered vehicles could be expected to significantly reduce CO_2 emissions. Furthermore, based on this simulation analysis, with PV onboard, roughly 40% of vehicles could be driven without ever requiring external charging[2].

According to the calculations by NEDO[3], by increasing battery capacities to 40 kWh and improving vehicle energy consumption rate to 12.5 km/kWh, roughly 70% of passenger vehicles in Japan could potentially drive solely on solar energy.

In this way, PV-powered passenger vehicles could not only significantly reduce CO_2 emissions, but also reduce the charging frequency, making major contributions to the convenience of electric vehicles.

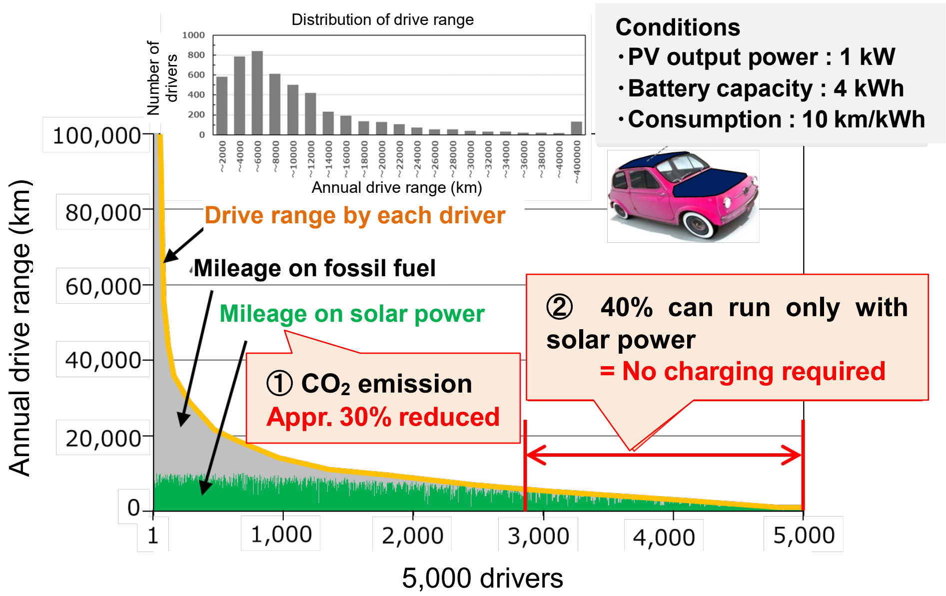


Fig. 2.1-2 Effect of onboard PV (Simulation Results)

2.1.3 Public Road Demonstration Driving: Generated Power and Possible Driving Distance

The rated output of PV-powered vehicles currently commercially available is approximately 200 W. This is significantly less than the PV that would yield the aforementioned CO_2 emissions reductions. Public road trials were therefore performed using vehicles with ultra-high-efficiency PV cells with a rated output of roughly 860 W. These trials investigated the amount of PV power that could be generated and the distance that could be driven by this PV, which leads to CO_2 emissions reductions.

Regardless of the capabilities of the PV, the effect of onboard PV was affected significantly by the actual driving patterns. Table 2.1-1 shows the driving patterns that were used in the demonstration driving. These were selected to reflect real-world driving patterns from actual market by actual users.

Table 2.1-1 Driving patterns used in demonstration driving

	Usage	Driving range (km/day)	Patterns
A	Highway	70	12AM 8:30AM Outdoor parking 3:30PM 11:59PM; Driven, Driven
B	Neighborhood driving (shopping、 pick-up/drop-off)	5	12AM Outdoor parking 10AM 11:30AM Outdoor parking 11:59PM; Driven, Driven
C	Commute	15	12AM 8AM Outdoor parking 5PM 11:59PM; Driven, Driven
D	City area	15	12AM Outdoor parking 10AM Outdoor parking 3PM Outdoor parking 11:59PM; Driven, Driven

A representative example of the results of the trials is obtained under driving pattern A, shown below. Pattern A consists of driving 35 km in the morning and 35 km in the afternoon (for a total driving distance of 70 km in a day). The power consumption rate for this pattern was measured as roughly 10.1 km/kWh.

Fig. 2.1-3 shows changes in the amount of PV generated power by the demonstration vehivle and its remaining battery level (state of charge, or SOC). The SOC fell from 66% to 24% as a result of the morning drive. But during the outdoor parking after driving (from 10:00 a.m. to 3:00 p.m.), the PV charged the batteries, restoring the SOC to 58%. This data was acquired in June 2020, and on that day the onboard PV generated approximately 4 kWh of power, and it was experimentally confirmed that the power generated by the PV could be used to drive 30 km per day.

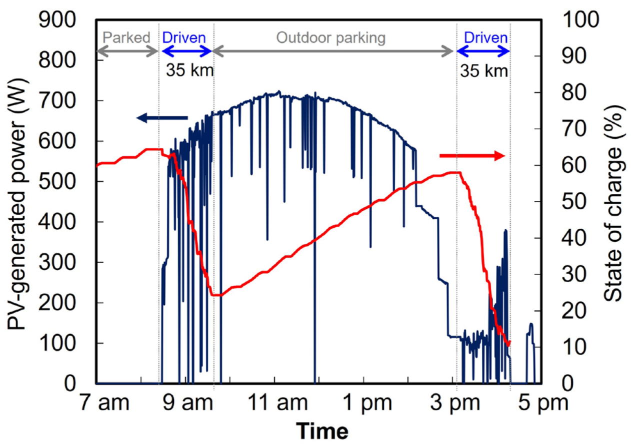


Fig. 2.1-3 Power generated by the PV on the demonstration vehicle and the changes in remaining drive battery level

Fig. 2.1-4 shows measurements of the driving distance using onboard PV derived power and solar irradiation per day. The amount of solar irradiation was determined by averaging the measurements taken in September 2021 from multiple pyranometers attached to the exterior of the demonstration vehicle. The driving distance by using PV power is proportional to the sola irradiation each day, and the constant proportionality was estimated at 5.9 (km/(kWh/m^2)). Tokyo, for example, receives approximately 1,200 kWh/m^2 of solar irradiation per year. A vehicle with an 860 W PV system would therefore, theoretically, be able to drive approximately 7,080 km per year.

Based on the above, it would be reasonable to conclude that the demonstration driving experimentally confirmed the effect of mounting PV on vehicles.

Furthermore, based on these results, and using solar irradiation data in Nagoya for estimation, it was found that CO2 emissions could be reduced by 62%[4].

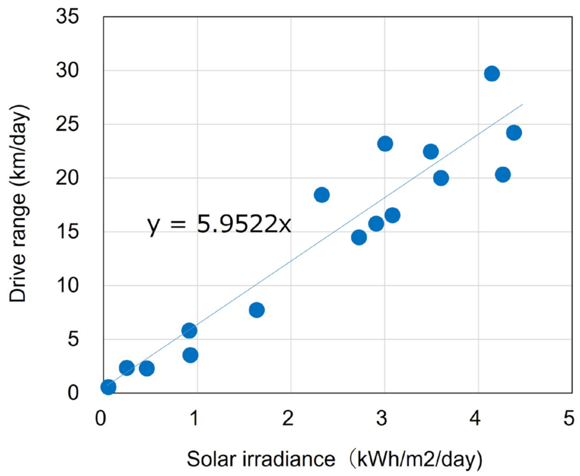


Fig. 2.1-4 Relationship between driving distance by solar energy and solar irradiation

2.1.4 Issues and Prospects

Based on the above, it has been experimentally confirmed that mounting PV on vehicles could reduce CO_2 emissions and the charging frequency, as had been expected. In the future, it will be important to closely examine the differences in the benefits of using onboard PV based on the differences in the usage patterns of vehicles.

Vehicles that can run on solar energy have only recently made commercially available, and hopes are high for future technological advances. As PV-powered vehicles become prevalent in the future, and further, if the applications such as V2H and V2G are actively implemented, the PV on vehicles will not only be used to generate power for driving, but will also play a major role in achieving a carbon neutral society as a part of society's infrastructure. Onboard PV and the related technologies must be actively developed in order to create a society in which people can lead richer and safer lives.

2.2 Installation of PV Systems on Electric Vehicles: Evaluation of Power Generation, Charging Frequency Reduction, and Performance against Fluctuations in Solar Irradiation

2.2.1 Objectives of Demonstration and Vehicle Specifications

A demonstration driving was initiated on mounting a PV system on an electric vehicle, using the power generated by the PV to charge the vehicle's drive batteries and then driving the vehicle. Data regarding power generation performance was acquired during parking and public roads driving in order to perform the followings: 1) assessment of the actual amount of power generated and the actual reduction in charging frequency, 2) evaluation of performance against partial shading, and 3) evaluation of MPPT performance while driving.

Figs. 2.2-1 and 2.2-2 show the appearance of the demonstration vehivle and an overview of the PV system. Table 2.2-1 shows the vehicle's specifications. A Nissan eNV200 was used as the base vehicle, and the power generated by the PV system was stored in a 40 kWh vehicle drive battery. PV panels made up of multiple modules were installed in three locations: the roof, the bonnet, and the tailgate. The roof had six PV panels and the bonnet and tailgate each had two PV panels, with each panel consisting of two PV modules. Each of these modules consisted of multiple unit cells connected in a series-parallel configuration, and each module had its own connected MPPT converter for power control. The PV cells used were III-V compound triple junction PV cells with a module conversion efficiency of 31.17%, and were developed by Sharp Corporation[5]. The maximum module voltage, even when sunlight is strongest during the year, was kept below 60 V for safety. The roof also had a pyranometer for measuring solar irradiance. A converter system was connected between the PV panels and the drive batteries to convert power, controlling the power generation of the PV panel and converting the voltage to supply power to the drive batteries.

Fig. 2.2-1 The demonstration vehicle

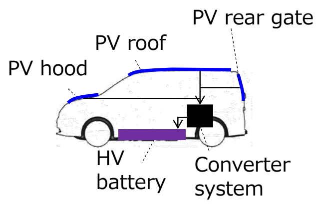


Fig. 2.2-2 The demonstration vehicle's PV system

Table 2.2-1 Specifications of the PV system installed in the vehicle

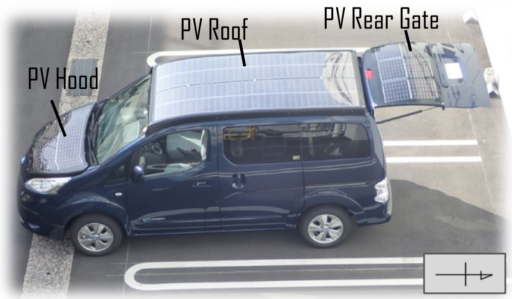
Base vehicle (eNV200) specifications			
Vehicle type	BEV		
Battery capacity	40 kWh		
PV panel specifications			
	Roof	Hood	Rear gate
PV cell structure	GaAs-based 3-layer tandem		
PV cell manufacturer	SHARP		
Nominal PV output	1,150 W		
No. of modules	6	2	2
Angle to the horizon	0–20°	20°	0-20°(open) 80°(close)

2.2.2 Assessing Actual Capabilities - Amount of Power Generated, Possible Driving Distance, and Reduction in Charging Frequency

(1) Annual Power Generation and Possible Driving Distance

(i) Experiment and calculation conditions

The amount of power generated by the demonstration vehicle was evaluated over the course of a year. In order to determine the maximum capabilities of the on-board PV system, measurements were performed by opening the tailgate such that all of the PV panels were oriented horizontally[6], as shown in Fig. 2.2-3.



Location
: Yokosuka, Kanagawa Prefecture, Japan
Vehicle placement
: Parked facing south, rear gate opened horizontally
Weather
: Mainly measured on days with no rainfall

Fig. 2.2-3 Vehicle during power generation evaluation

The actual results of daily measurement were integrated with the calculation method shown below to calculate the potential monthly and yearly possible EV driving distances given the amounts of power generated. Specifically, the following formula was used to calculate the possible EV driving distance that could be achieved from the amount of energy generated per day (Eg), summed over the course of a year.

Possible EV driving distance (amount of power generated per day) = {amount of power generated per day Eg x c) electric fuel economy} Eg = {a) daily solar irradiation Er x b) solar-power generation coefficient}

a) Daily solar irradiation (Er)

- This was calculated using the information in the NEDO solar irradiation database (METPV-11)[7].
- Solar irradiation data for representative years (average year, high-irradiation year, and low-irradiation year) was available for various locations in Japan (837 locations) for a 20-year period (1990 to 2009). Data regarding solar irradiation over the course of an entire year could be used on an hourly basis. (Fig. 2.2-4).

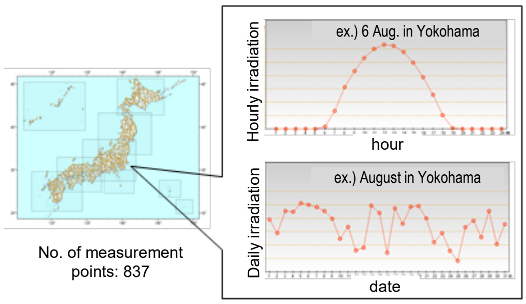


Fig. 2.2-4 NEDO solar irradiation database[7]

b) Solar-power generation coefficient (relationship between the solar irradiation (Er) and the amount of power generated (Eg))

- The amount of power generated by the PV during the power generation evaluation experiment and the solar irradiation recorded by the on-board pyranometer were measured and the correlation was calculated (Fig. 2.2-5).
- The solar irradiation (Er) and the amount of generated power (Eg) were generally proportional, regardless of the weather or time of year, so a linear approximate equation was used for calculations.

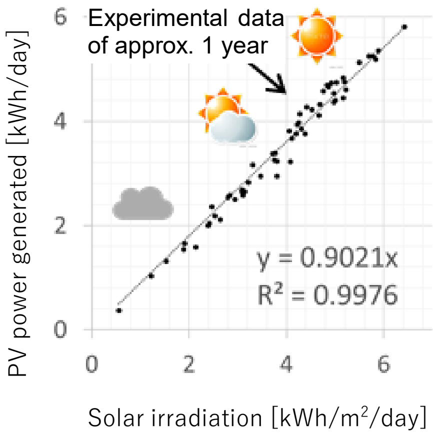


Fig. 2.2-5 Relationship between the amount of energy generated and solar irradiation during power generation evaluation

c) Electric fuel economy

- The electric fuel economy from public road demonstration driving was used. The annual average electric fuel economy is 6 km/kWh, but due to differences such as air conditioner usage frequency, electric fuel economy varies by season, so the calculations reflect these quarterly fluctuations.

(ii) Calculation results for annual power generation and possible EV driving distance

Fig. 2.2-6 shows the amount of power generated each month and the maximum daily power generated within the month. These calculations were based on data from the solar irradiation database for an average year in Yokohama. The weather on the days with the daily maximum generated power were predominantly sunny, and the data produced a smooth curve that reflects the effects of the sun's altitude in the sky. Furthermore, the data for the monthly amount of power generated over the course fell below the maximum daily power generation graph's curve at two points: June and October. This can be attributed to the rainy season and autumnal rain fronts.

Fig. 2.2-7 shows the possible EV driving distance based on the amount of power generated each month. It can be deduced that the total EV driveable distance was roughly 7,100 km per year, or an average of roughly 20 km per day. As Fig. 2.2-6 shows, the months with the highest power generation amounts were July and August, but the months with the longest possible EV driving distances were April and May. This is because of seasonal differences in electric fuel economy and differences in the number of sunny days. The shorter possible EV driving distance in June can be attributed to the prevalence of cloudy days during the rainy season. Also, the possible EV driving distance in winter is roughly half that of the summer.

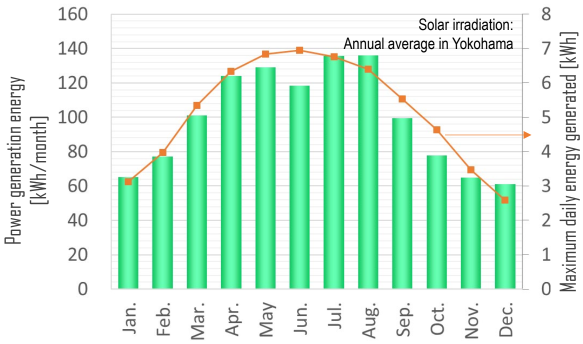


Fig. 2.2-6 Monthly power generation and maximum daily power generation

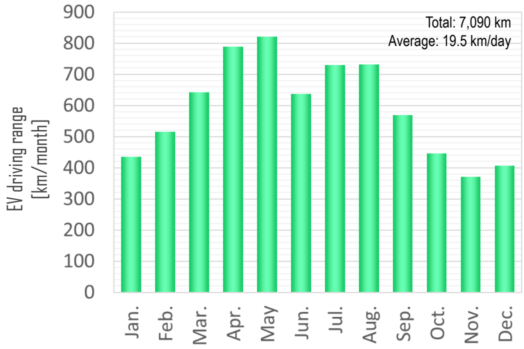


Fig. 2.2-7 Possible EV driving distance per month

(2) Effect of Reducing the Frequency of Charging

Using PV to charge EV's driving batteries is expected to reduce the frequency of charging. The demonstration vehicle was used to validate the benefit.

(i) Calculation method and calculation conditions

The driving pattern used was "C: Weekday commuting use only" (Table 2.2-2), based on the representative vehicle usage patterns listed in the PV-Powered Vehicle Strategy Committee Interim Report (January 2018)[3]. One-way commuting distances were used as a parameter (10, 15, 20, and 25 km), and the annual number of charges for scenarios with and without the use of PV were calculated.

Table 2.2-2 Excerpt of representative car usage Patterns[3]

Pattern	Type	Driving distance per journey (km)	User image
C Weekday use	C-1 Long-distance commuting	50 km for 5 days (weekdays)	Use only on weekdays for commuting to distant workplace, etc.
	C-2 Short-distance commuting	15 km for 5 days (weekdays)	Use only on weekdays for commuting to nearby workplace, etc.

When starting with day n, the formula for determining the battery energy (state of charge (SOC)) for day n+1 is as shown below. The calculation conditions were as shown on Table 2.2-3.

$En_{Ba\_n+1} = En_{Ba\_n} - En_{Dr\_n} + En_{So\_n}$

$En_{Dr\_n} = Di_{Dr\_n} \div Ef_{Dr\_n}$

$En_{So\_n} = Ef_{Sun\_n} \times Ef_{So\_n}$

If $(En_{Ba\_n+1} < En_{Ba\_min})$ …En_{Ba_n+1} is overwritten with En_{Ba_max} (number of charges + 1)

If $(En_{Ba\_n+1} > En_{Ba\_max})$ …En_{Ba_n+1} is overwritten with En_{Ba_max} (simulating a full charge)

- En_{Ba_n} : Battery energy on day n
- En_{Dr_n} : Energy consumed by driving on day n
- En_{So_n} : PV energy generated on day n
- Di_{Dr_n} : Distance driven on day n
- Ef_{Dr_n} : Electric fuel economy on day n
- Ef_{Sun_n} : Solar irradiation on day n
- Ef_{So_n} : PV conversion efficiency on day n
- En_{Ba_max} : Maximum battery energy charge
- En_{Ba_min} : Minimum battery energy discharge threshold

Table 2.2-3 Battery energy calculation conditions

Solar irradiation	NEDO solar irradiation database (Yokohama, average year)
PV conversion efficiency, electric fuel economy, and driving distance	Used values determined based on trials
Initial battery energy level	24 kWh
Maximum battery energy charge	40 kWh
Minimum battery energy discharge threshold	8 kWh

(ii) Results of the calculation of effectiveness in reducing the frequency of charging

Fig. 2.2-8 shows trends in the annual battery energy calculation values over the course of the year for a commuting distance of 10 km (round-trip distance of 20 km). On weekdays, the amount of energy consumed by driving exceeds the amount of PV generated, so the battery energy level decreases. However, on weekends, the PV generated is directly used for charging, so the battery energy level increases. During winter (December and January), the weekday battery energy decrease and the weekend battery energy increase were generally equal, so the conditions were just sufficient to operate the vehicle without charging. For seasons other than winter, the increase in battery energy on weekends exceeded the decrease in battery energy on weekdays, so the battery charge level remained near its maximum (40 kWh). This shows that there was a surplus of PV power. Furthermore, the vehicle never dropped below its minimum battery energy discharge threshold over the course of the entire year, indicating that the vehicle could be used without ever requiring charging.

Fig. 2.2-9 shows trends in the annual battery energy calculation values over the course of the year for a commuting distance of 25 km (round-trip distance of 50 km). Although battery energy amounts increased on weekends, they decreased by a greater amount during the week. As a result, there are several occurrences that the battery energy reached the minimum battery energy threshold. This indicates that in this scenario, charge-free operation would not be possible.

Fig. 2.2-10 shows the difference in the charging frequency over the course of the year for one-way commuting distances of 10 to 25 km, comparing the scenarios with and without PV. This shows that, although the commuting distance for which charge-free operation is possible was 10 km or under, even for people who commute more than 10 km, the annual charging frequency could be reduced considerably. For example, for a commuting distance of 25 km, the number of charges per year could be reduced by roughly 48%.

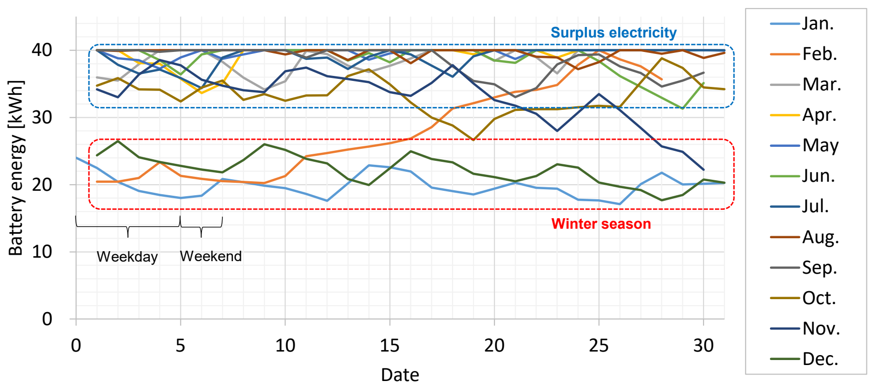


Fig. 2.2-8 Battery energy trends for commuting 10 km

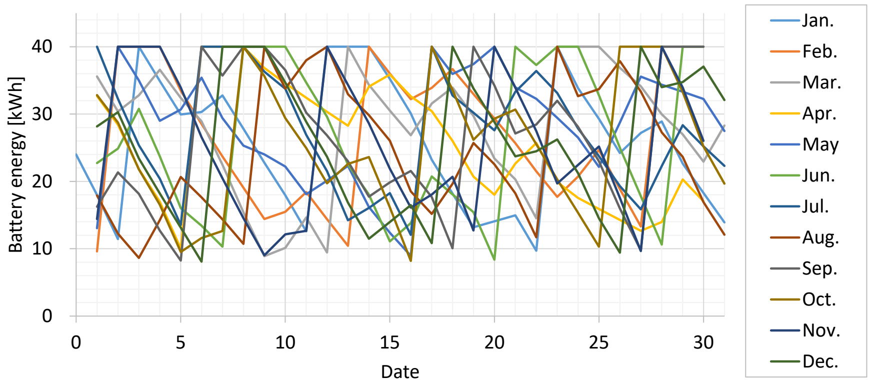


Fig. 2.2-9 Battery energy trends for commuting 25 km

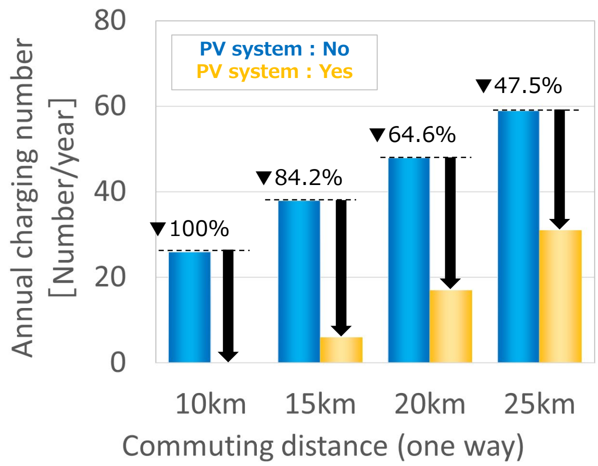


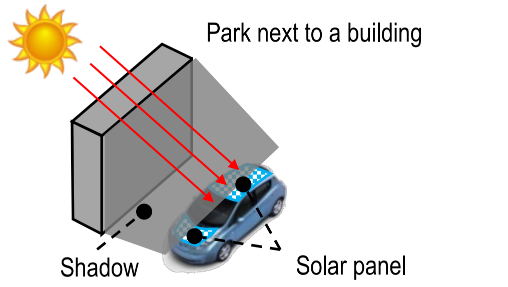
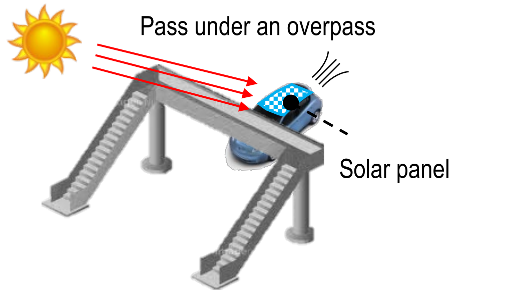
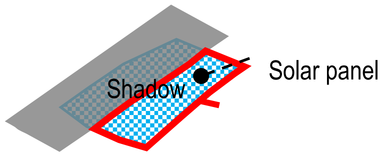
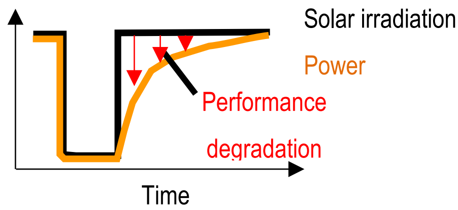
Fig. 2.2-10 Annual battery charging frequency during commuting

2.2.3 Evaluation of Performance in Relation to Fluctuations in Solar Irradiation

(1) Issues Related to Fluctuations in Solar Irradiation

One of the unique challenges faced by on-board PV systems is that, due to being installed on the moving vehicles, solar irradiation received can be obstructed in unpredictable shapes and timings, leading to frequent fluctuations in solar irradiation. Situations in which there are fluctuations in solar irradiation include i) when a part of the on-board PV is in the shade and ii) when there are sudden fluctuations in solar irradiation while driving (Table 2.2-4). Methods for dealing with these different forms of fluctuations in solar irradiation are described below.

Table 2.2-4 Situations in which fluctuations in solar irradiation occurs in onboard PV

	i) Partial shade	ii) Quick change of solar irradiation
Scene		
Issue	 Performance degradation under sunlight due to influence of PV panel under the shadow	 Delay of generation power due to solar irradiation change

(2) Response to Partial Shading

(i) Countermeasures

Fig. 2.2-11 shows the converter system. In order to deal with partial shading, the PV modules are segmented and each is provided with its own converter. This structure makes it possible to perform Maximum Power Point Tracking (MPPT) control for each individual PV module. The step-up function for the high voltage system is provided by a subsequent converter. Therefore, even if there is partial shading, etc., the PV modules that are not in the shade will not be affected by those that are in the shade, and the subsequent converters connected to them are able to step up the voltage[8].

Fig. 2.2-12 shows the connection configuration of PV cells in each PV module. Each string is made up of 16 PV cells connected serially, and 11 of these strings are connected in parallel, making up the PV module. Due to this connection configuration, when shading occurs like Shadow A in Fig. 2.2-12, the PV cells covered in shadow will be in parallel, so the PV module voltage will stay the same but the current will drop (Fig. 2.2-13). In contrast, when shading occurs like Shadow B, the PV cells covered in shadow will be in series direction, so as the area of the shadow increases, the PV module voltage will drop but the current will stay the same. Keeping the voltage the same makes it possible to maintain the optimal step-up ratio within the converter, so the PV would be more robust when shaded by a shadow such as Shadow A. When a vehicle is in motion, Shadow A-type moving shadows are dominant, so cells were arranged to provide robustness for this direction of shadows.

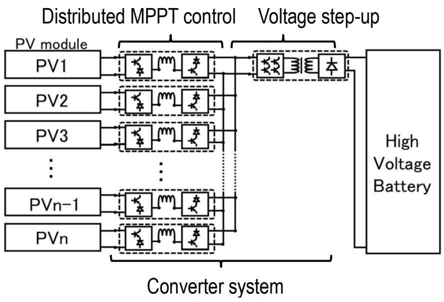


Fig. 2.2-11 Overview of the converter system[6]

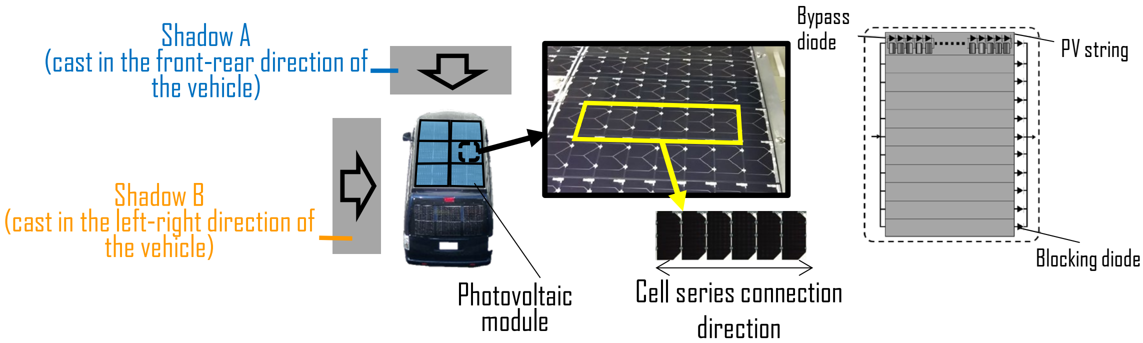


Fig. 2.2-12 PV cell layout and relationship between its positioning in relation to the vehicle body and shadow

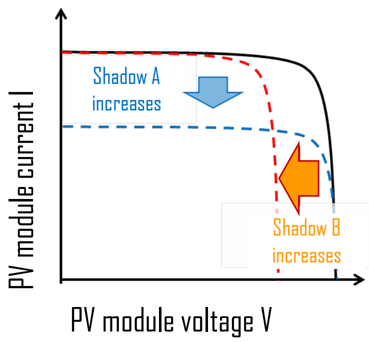


Fig. 2.2-13 PV module IV characteristics

(ii) Evaluation results

For the two types of shadows shown in Fig. 2.2-12, artificial shadows using shading objects were created and trials were performed. Shadow A represented a shadow that moves from the front toward the rear of the vehicle, while Shadow B represented a shadow that moves from the left toward the right of the vehicle.

Fig. 2.2-14 shows the relationship of the normalised roof-generated power to the areas of Shadows A and B. This normalisation is based on the roof-generated power when the shadow coverage percentage is 0%. As the shadow area of Shadow A increased, the normalised roof-generated power fell linearly, but the normalised roof-generated power fell in steps for Shadow B. Compared to Shadow A, the decline in generated power for Shadow B is greater.

Fig. 2.2-15 (a) shows the normalised PV module power, voltage, and current when the shadow area of Shadow A is 17% (1/6). Half of PV1 and PV4 were in the shade, so the module current was halved, but the shadow covered the PV cells in their parallel direction, so the module voltage stayed the same. As the results show, module power only fell for the part covered by the shade.

Fig. 2.2-15 (b) shows the normalised PV module power, voltage, and current when the shadow area of Shadow B is 12.5% (1/8). 1/4 of PV1, PV2, and PV3 were in the shade, and the module voltage fell by more than 1/4 of the voltage when there was 0% shadow coverage. The current also fell slightly from the current when there was 0% shadow coverage. This is believed to be because when the current passed through the bypass diodes for the part in shade, the voltage fell, and the current was dropped during the transition to a new optimal operating point through MPPT control.

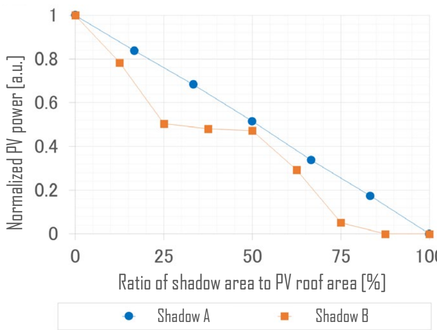


Fig. 2.2-14 Shade coverage percentage and normalised roof-generated power[8]

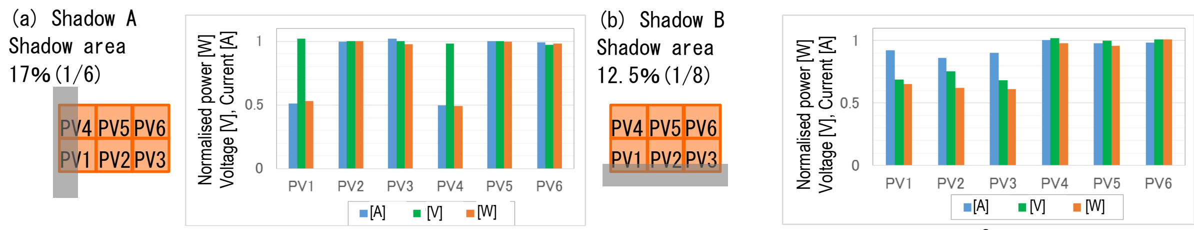


Fig. 2.2-15 Normalised PV module power, voltage, and current[8]

(3) Response to Transient Fluctuations in Solar Irradiation

(i) Countermeasures

For the converter system shown in Fig. 2.2-11, Maximum Power Point Tracking (MPPT) control was used to constantly update the operating point of each PV module. The operating points were determined by using the ordinary hill climbing method to change the operating voltage of the PV module and track the operating point that produces the greatest power. When there are complex fluctuations in solar irradiation occur over short durations, such as when the vehicle passes under a tree's shadow on the side of the road, the voltage-current characteristics of the PV module undergo multiple changes as the system looks for the maximum power point. It can take some time to find the maximum power point, resulting in power generation opportunity losses. Improving the control tracking performance in situations in which there are frequent solar irradiation changes by limiting the voltage search range of the MPPT control was attempted.

(ii) Method (evaluation through driving on public roads)

MPPT control was evaluated in locations where there were trees on both sides of the road, like that shown in Fig. 2.2-16. Driving on these roads involves repeated switching between sunlight and shade, making it hard for MPPT control to track operating points. The trial method consisted of changing the initial search voltage as shown in Fig. 2.2-17 and measuring the MPPT achievement rate (see the formula below). The MPPT achievement rate is the rate of actual generated PV power to the amount of PV power that would be generated at the MPP estimated based on solar irradiation. It indicates the level of performance of the MPPT control.

Fig. 2.2-16 Evaluation scene

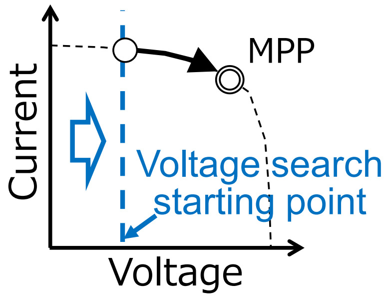


Fig. 2.2-17 MPPT control initial search voltage

$$AR_{MPP} = \frac{P_{AVE}}{S_{AVE}} \div R_{MPP} \times 100$$

AR_{MPP}	: MPPT achievement rate
P_{AVE}	: Average PV generated power
S_{AVE}	: Average solar irradiation
R_{MPP}	: Amount of PV power generated at MPP relative to solar irradiation

(iii) Results

Fig. 2.2-18 shows the relationship between the MPPT achievement rate and the MPPT control initial search voltage. As the figure shows, the higher the MPPT control initial search voltage is raised, the higher the MPPT achievement rates. This indicates that raising the MPPT control initial search voltage to limit the search range improves the MPPT control response. Moreover, when the MPPT control initial search voltage was raised to 40 V, the MPPT achievement rate dropped significantly, presumably because the MPP voltage is roughly 38 V, making it impossible to operate constantly at the MPPT. Consequently, it is found that an MPPT achievement rate of 97% or greater could be achieved by setting the initial search voltage between 20 and 35 V.

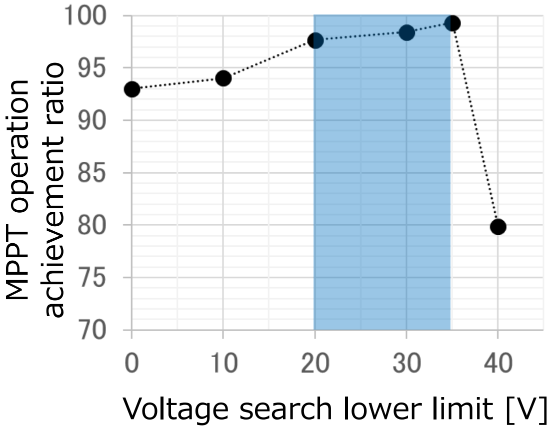


Fig. 2.2-18 Relationship between the MPPT control initial search voltage and the MPPT achievement rate[6]

Fig. 2.2-19 shows the results of the evaluation when the demonstration vehicle passing by trees along the side of the road. The graphs show the relationship between solar irradiation and the amount of power generated by the PV roof at the evaluation locations indicated above when searching range of MPPT control was set to the entire region (left) and when it's limited (right). When the search range was set to the entire region (left), the search for the MPP took a large amount of time, so even if solar irradiation returned to normal levels when the vehicle moved out from the shade to the sunlight, the amount of power generated by the PV roof did not recover completely. However, when the search range was limited (right), the amount of power generated by the PV roof fully recovered when solar irradiation returned to normal levels. In this way, appropriately limiting the MPPT control searching range successfully improved MPPT control tracking performance.

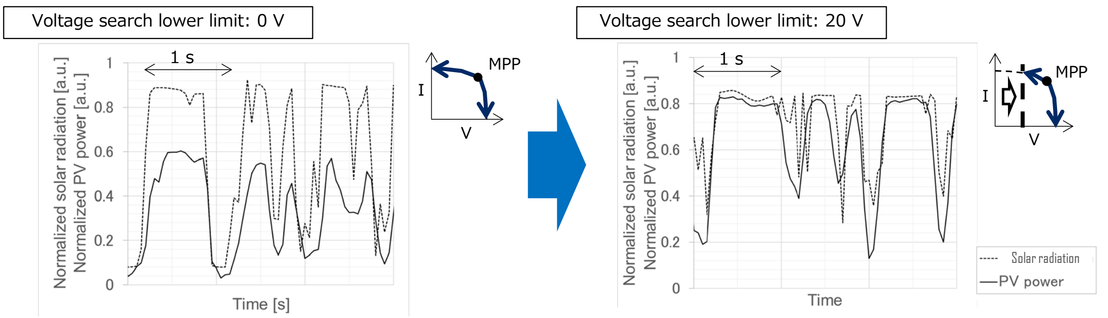


Fig. 2.2-19 Relationship between solar irradiation and the amount of power generated by the PV roof[6]

2.2.4 Issues and Prospects

The market for electric vehicles that use PV energy is still in its nascent stage, and further accumulation of actual driving data should be obtained.

System designs tailored to the characteristics of shadows on vehicles, as reported in this section, is required. But there are countless potential shading patterns, so it will be vital to obtain driving data under diverse conditions to determine which pattern or patterns are predominant. Future studies will also include investigations of changes in the long-term performance and functional transitions of onboard PV power systems.

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Chapter 3: Research for Realisation of PV-Powered Vehicles

Chapter 2 presented findings obtained so far from demonstration driving of PV-powered vehicles performed by automotive companies.

There are differences in required technologies, requirements, power generation characteristics, etc., between PV on a vehicle and conventional fixed PV installed on roofs or the ground (after this referred to as "conventional PV") (Table 3-1)[1].

This chapter overviews research from these perspectives for the realisation of PV-powered vehicles.

Table 3-1 Examples of differences between conventional PV and vehicle-mounted PV

Item	Conventional PV	Vehicle-mounted PV
Surrounding shade Use of sunlight	Cells are installed to avoid the shade Cells are positioned and angled for maximal use of sunlight	Cells are frequently in the shade Cells are affected by sunlight being cut off or reflected by nearby buildings
Partial shading Dynamic shade	Little impact	Large impact
Flatness/ curvature	Flat Sunlight strikes the entire surface uniformly	Curved Sunlight does not strike the surface uniformly Susceptible to cracking when bent
Environmental testing	Testing primarily for long-term degradation in outdoor environments IEC standards	Testing to ensure basic performance and safety even under severe conditions ISO standards, JASO standards

3.1 Impact of Surrounding Environment on Solar Irradiation and Amount of Power Generated

Databases such as Monsola predict the amount of power conventional PV systems generate. However, the data in these databases assume that the direct irradiance, uniform aerial horizontal irradiance, and the sum of multipath reflections between the surface and the sky will match the intensity of solar radiation striking the fixed panel.

However, onboard PV is subjected to shadows from various objects like buildings, houses, telegraph poles, road signs, trees, and power lines, all varying in size and direction. In other words, the surface cannot be assumed to be uniform, so the methods and formulas used for conventional PV systems cannot be applied as-is[2].

In terms of direction, because the front and rear directions of roads are open spaces, shade tends to be infrequent, but shade often falls on vehicles from the sides[3]. The vehicle's driving direction is not fixed, so the distribution of shadows that affects insolation and the resulting distribution of solar irradiation cannot be handled using a fixed, ground-based coordinate system. Instead, a local coordinate system fixed to the vehicle must be used. Further, the vehicle-mounted PV has a non-axisymmetric curved surface, so even when exposed to uniform light, the received solar irradiation will differ on the panel's left, right, front, and rear sides. For this reason, it is also vital to build a new light incidence and power generation model using a local coordinate system fixed to the vehicle body[4]. Fig. 3.1-1 shows the concepts of the different types of partial shading (the transient partial shading discussed in the previous section and the concept of uneven irradiation over a curved surface with the same effects)[5].

Parked in direct sunlight
Mismatch inherent to curved surface

Partial shading (when parked)
Mismatching unique to the partial shading

Dynamic shading (while driving)
Mismatching that occurs when shadows are also moving

Fig. 3.1-1 Conceptual diagram of negative impact of curved surfaces, partial shading, and dynamic shading on output

Solar irradiation in the surrounding environment of the vehicle and the impact it has on the power generation are shown using the steps below.

- Measurement and standard modelling of the direction and distribution of elevation angles of the buildings that cast shadows around the vehicle
- Measurement of the solar intensity based on the above shadow distribution (model verification)
- Measurement of direction and distribution of elevation angles of partial shading sources and determination of their impact on the power generation

3.1.1 Distribution of Buildings and Other Structures Casting Shadows around the Vehicle

(1) Method

A security camera with a fisheye lens was mounted on the roof of a vehicle and was driven through the city of Miyazaki (using a route that included roughly equal open areas, residential areas, and building areas). This was used to determine the direction and distribution of elevation angles of shadow sources, such as buildings and telegraph poles, from the perspective of a vehicle roof.

Image processing was performed on the upward-facing fisheye video taken from the vehicle's roof to perform binary separation of the video into obstructions, such as buildings and open sky. Coordinates (polar coordinates) of the outlines of buildings, etc., were captured to investigate the distribution of elevation angles. When calculating the horizontal solar intensity on the roof, the azimuthal distribution of the obstructions does not need to be considered.

Concerning the distribution of partial shading, contour extraction can be performed after the binary separation above, and the distribution of collections of edge points can be investigated to analyse the occurrence probabilities. However, this only determines whether or not partial shading exists, and the results do not indicate the impact the size or shape of the partial shading has on the amount of power generated. To determine this, the impact (partial shading factor (PSF)) must be measured separately. When discussing the amount of annual solar power generation, the PSF distribution can be averaged and considered separately from other factors, so these figures can be calculated as anticipated values.

(2) Results

The probability of a building or other nearby object blocking the sunlight falls as the sun's angle of elevation increases. Therefore, this data was applied to a growth curve to model the distribution. The cumulative logistic curves were a good fit for various surrounding environments. Broadly, the shade environments around roads could be divided into three categories: building, residential, and open areas. Standard shade probability functions were defined for each (Fig. 3.1-2). The angles of elevation of sunlight obstructions that create shadows tended to be higher for the left-right direction of the vehicle (particularly in buildings and residential areas) than for the front-rear direction of the vehicle (direction of travel), so shade probabilities must be considered separately for each direction.

<Buildings areas> <Residential areas> <Open areas>

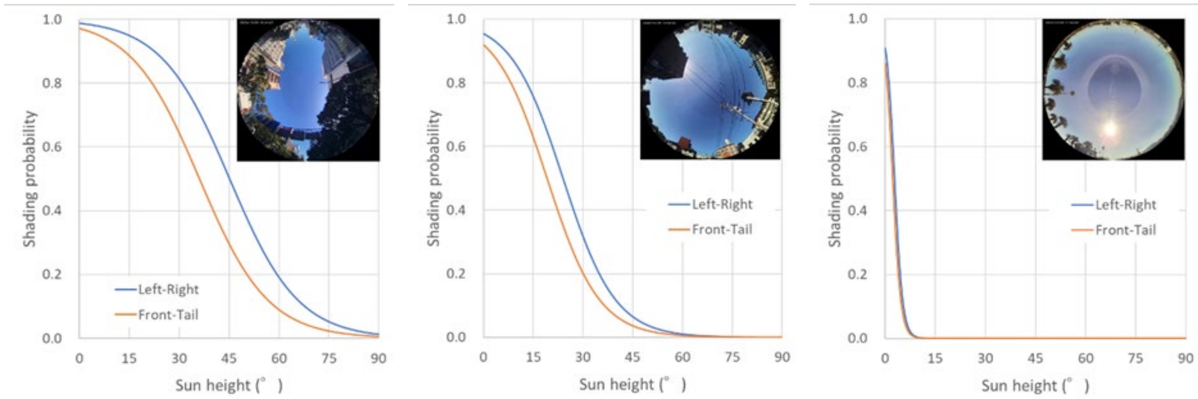
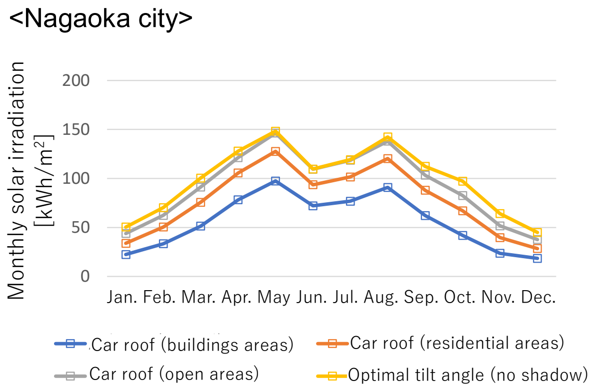


Fig. 3.1-2 Probabilities of buildings or other nearby objects blocking sunlight (Standard distribution of elevation angles for each zone)

This can predict insolation amounts for various driving areas in various regions. For example, Fig. 3.1-3 shows the monthly solar irradiation of a vehicle's rooftop PV installation area driven through residential areas in Nagaoka City (Niigata Prefecture) and Miyazaki City (Miyazaki Prefecture). In order to compare data with that from conventional PV, the solar irradiation in an optimal direction and tilt angle in shade-free areas were plotted simultaneously. Shadows cast by nearby buildings, etc., cause the solar irradiation of roof installation surfaces to fall roughly 70% in residential areas (varying by season and region).



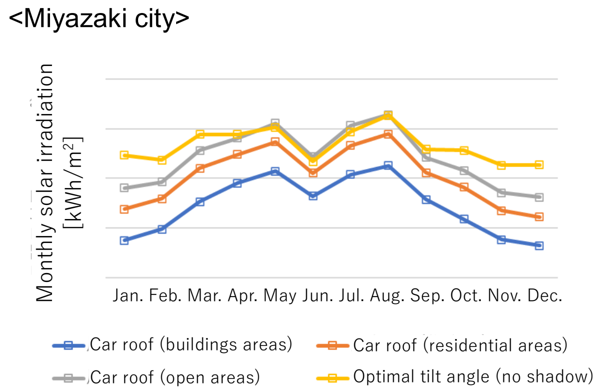


Fig. 3.1-3 Results of calculation of daily solar irradiation for the rooftop PV installation area of a vehicle driven through residential areas

3.1.2 Verification of the Solar Intensity Model Based on the Shade Distribution

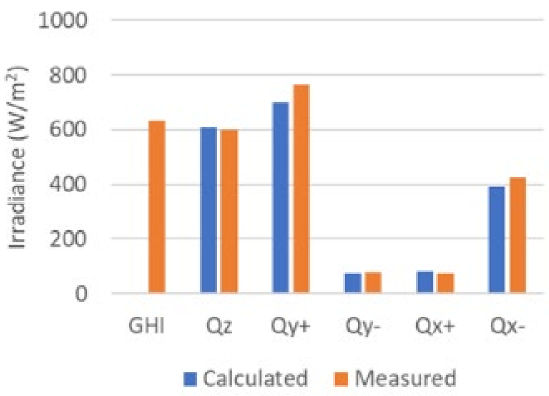
(1) Method

Pyranometers were attached to a vehicle's roof, front, left side, right side, and rear, in the directions of five orthogonal axes. Their data was compared against the computed insolation for each axis, considering the reflections from building walls, etc., derived from the shape of the open sky in the upward-facing fisheye video. This was done to verify if, irrespective of the driving direction or the shade conditions in the driving area, the 3D irradiation of the area around the vehicle (the solar intensity on each side of the vehicle) matched the values calculated using the model[6].

Measurement was not just performed on the roof but on five orthogonal axes of the vehicle: the top, the front, the left side, the right side, and the rear. The calculated values were checked for conformity with the measurement values for each side. This was done to eliminate the possibility that the roof evaluation figures just happened to match on the day of the measurement but not on other days or different routes (resulting in erroneous verification results).

(2) Results

The above verification found that the measured solar intensity approximately matched the solar intensity calculated based on the observed open-sky shapes. This was true for all driving directions (the orientation of the sun in the local coordinates of the vehicle), all driving zones (buildings, residential, open, etc.), and all five axes (Fig. 3.1-4). GHI in the figure represents the solar intensity on a horizontal surface under the open sky near the driving area.



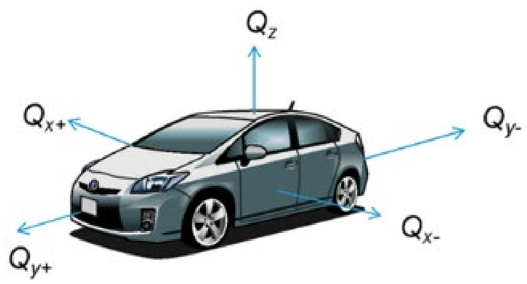


Fig. 3.1-4 Results of measurement of insolation on each side of the vehicle and the comparison against 3D irradiation (non-uniform sunlight obstruction) model

3.1.3 Measurement of Direction and Distribution of Elevation Angles of Partial Shading Sources and the Impact on the Power Generation

For partial shading, as well, analysis of fisheye video was used to calculate its occurrence probability at specific sun elevation angles. However, the impact of partial shading on power generation is highly dependent on the shape and size, and is also affected by the curvature of the vehicle body and the internal wiring (string structure) of the modules. Therefore, the probability of partial shading alone is not enough to calculate power output[7].

However, when discussing monthly or annual amounts of power generated, these amounts can be calculated by representing the above disturbance factors as expected values. For example, if a two-string structure (MPPT x 2) was used for a typical curved roof, and no excessive bending stress was placed on the cells at the centre of the vehicle roof (80% cell coverage), a good approximation could be determined by applying a compensation coefficient of 0.9, which also includes the curvature loss discussed later. It is essential to note that this loss tends to increase when using a vehicle with exceptional aerodynamics for improving electric fuel economy. Furthermore, this coefficient was calculated based on expected values, so it is a compensation coefficient for use in determining the amount of power generated over an entire year (with random driving times, driving durations, and directions). It is, therefore, essential to remember that this coefficient cannot be used to correct power generation amounts on any specific date/time (to correct power generation amounts for a specific date/time, one must instead perform two-dimensional calculations, such as creating a two-dimensional matrix that represents the open sky condition, applying direct sunlight incidence vectors and scattered sunlight incidence vectors, and performing integration using a sky-facing hemisphere).

3.1.4 Solar irradiation on Vehicle Roof for Each Surrounding Environment

Fig. 3.1-5 compares the power output per kilowatt of rated output for PV on vehicles and the amount of power generated by conventional PV (facing due south, at optimal tilt angle, and no shade). The following section, 3.2, will discuss how much PV surface area can be installed on vehicle roofs, but it was observed that the shade environment of the location where PV is placed has a more significant impact on the power generation than regional differences.

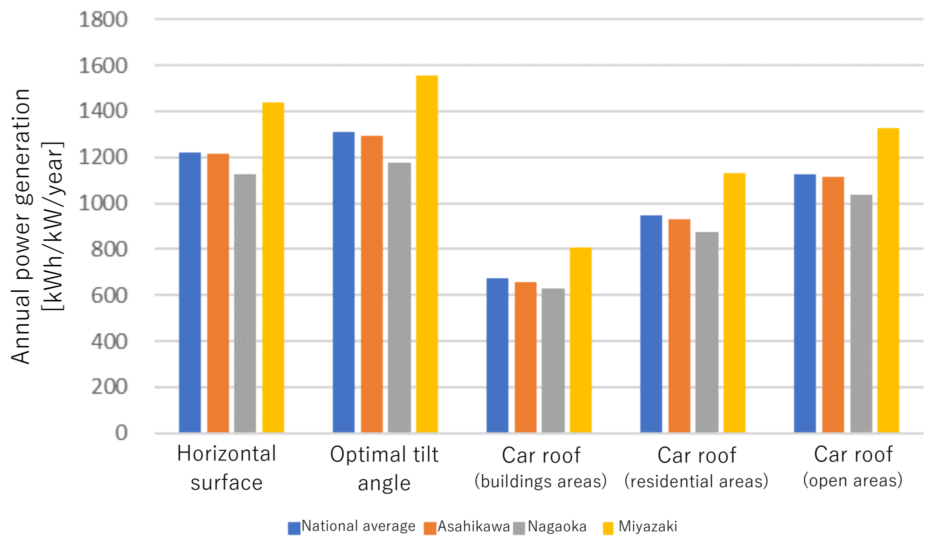


Fig. 3.1-5 Power generated by vehicle-mounted PV

3.1.5 Issues and Prospects (Impact of Surrounding Environment on Solar Irradiation and Power Generation)

The following have been identified as issues to be addressed.

- Global standardisation of energy ratings
  - ➢ The amount of energy that vehicle-mounted PV can supply links directly to the self-sufficiency rate of driving energy of PV-powered vehicles. It also serves as a standard in calculating cruising range, charging frequency, and carbon offsets (used in the carbon offset incentive system). Therefore, measurement and calculation methods must be fair and reproducible by all testing facilities and be agreed on globally and standardised. For this matter, the International Electrotechnical Commission (IEC) has launched a project team (PT600). The chairperson from Japan was selected, and Japan is leading these standardisation efforts[8,9,10,11].
- On-site measurement method standardisation
  - ➢ It is necessary to establish on-site measurement methods so third parties, including users, can verify the benefits of vehicle-mounted PV and PV-powered vehicles. As explained earlier, the amount of power generated by onboard PV cannot be discussed simply by extrapolating from the amount of power generated by conventional PV, so measurement methods, as well, must be formulated based on fair discussions. This topic is also being discussed under Japanese leadership at the PT600 above project team.
- Tandem PV cell power generation capacity measurement and modelling
  - ➢ Tandem PV (III-V, perovskite) is being developed for use in vehicle-mounted PV. The amount of power generated by this tandem PV varies in response to changes in the solar spectrum, and the impact can be significant in environments where shading occurs frequently, such as on vehicle surfaces. To accomplish their development goals, what is required includes technologies for rapidly measuring solar spectra during driving,

modelling power generation based on the results of those measurements, and verifying the model using vehicles with installed tandem PV[12,13].

- Eco-friendly navigation systems
    - Previous solar power generation predictions have exclusively used models (Monsola, METPV) that infer irradiation amounts based on region-specific climate conditions. In the case of vehicle-mounted PV, the type of area (buildings, residential, or open area) where the vehicle travels (or parks) (buildings, residential, or open area) is more important than their geographical area. Therefore, we believe that, rather than focusing on geographical differences, creating a database of solar irradiation compensation amounts for areas within XX km from reference points on major routes (such as National Route) would be more practical. Generally speaking, vehicles are oriented parallel to routes, so that a local coordinate system would be a good fit for the database.
- Formulating disaster prevention plans
    - Using V2E, electric vehicles could be a practical power source for aid stations and evacuation shelters in a disaster. However, supplying energy to these facilities would reduce the amount of energy available to vehicle owners, so there are debates about how smoothly supplying electricity for the public good would actually go even during times of disaster. If lifelines such as the power grid went down, charging stations would likely be incapacitated. PV-powered vehicles would be able to self-charge using solar irradiation, so these kinds of concerns would be minimal. As discussed previously, given advances in the modelling of the amount of power generated by onboard PV, quantitative discussions have begun regarding how power generated by onboard PV could be used to improve resilience in the event of large-scale disasters, using Monte Carlo simulations which include mathematical modelling of societal behavior (Photovoltaic Power Generation Technology Research Association (PVTEC) sixth vehicular photovoltaics webinar, February 24, 2022). There are hopes for formulating even more detailed plans concerning local disaster preparations integrated with stationary disaster relief equipment in community centres, nursing homes, schools, michinoeki (roadside stations), etc.

3.2 Statistical Assessment of Vehicle Body Shapes and Their Impact on Power Generation

3.2.1 The Need to Assess Vehicle Body Shapes

Generally speaking, vehicle bodies, including roofs, can be described using three-dimensional curved surfaces (non-developable surfaces). When PV panels cover vehicle bodies, those panels also become curved. However, the formulas and measurement methods used in determining the power generation performance of PV panels are based on the assumption of flat PV. The amount of power that can be generated from a curved PV panel cannot be determined from the total output of its cells, unlike in the case of a flat PV panel[1].

In the case of onboard PV, the impact of curvature on power output and the amount of power generated can be summarised using the following key points[5].

- Opening area loss: Due to the reduced opening area, even with the same solar intensity, the incident irradiation power decreases. In other words, because the surface area is more prominent than the projected area, the opening area captured by the PV panel tends to be lower than that of a flat surface.
- Self-shading
- Localised cosine loss: Even for parallel light rays that enter at the same angle, the angle of incidence on elements varies depending on the location on the curve, so the output from cells is not uniform, and mismatching loss occurs.

An important point to note is that these losses are not just affected by the curvature of the surface but also highly affected by the distribution of angles of incidence of the sunlight. This cannot be accounted for simply by multiplying by a constant. Instead, the shade cast by office buildings, houses, roadside trees, telegraph poles, power lines, and the like, along with the distribution of partial shading, as discussed in the previous section, must be considered when calculating compensation amounts.

Furthermore, compression stress on cells increases in locations with large degrees of curvature (locations with small curvature radii), which can lead to collapse failures. Therefore, some areas cannot be covered with PV cells. In other words, the coverage rate in these areas declines[14].

In this way, the impact of the car body's curved shape is extremely significant, and the shape varies widely by car models.

In the following sections, the assessment of vehicle body shapes and the quantification of their impact will be discussed. The existing methods for PV cannot be used to the performance or power generation of curved PV panels, which influence the value of vehicle-mounted PV panels. Various discussions of this topic are currently underway, and although they will not be covered by this report, Japan is taking the lead in the global standardisation of fair and reproducible testing methods, ways of indicating performance, and the like[11].

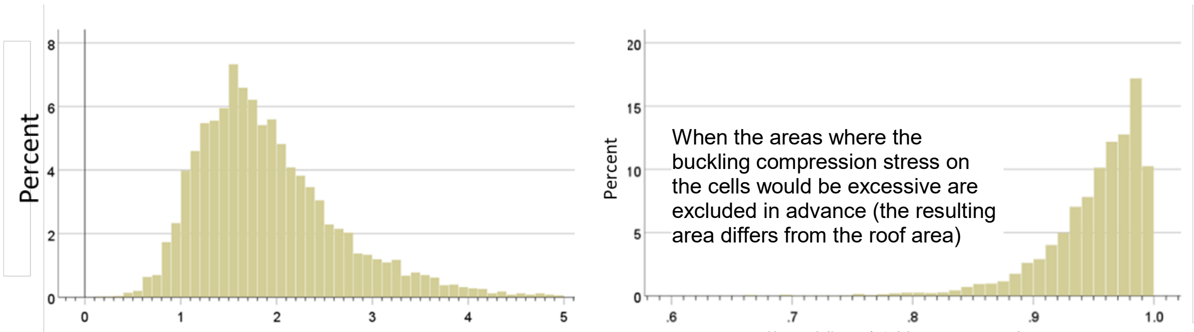
3.2.2 Statistic Methods for Assessing Vehicle Body Shapes

Data on the curvature shapes of commercial vehicles, such as CAD data, are not disclosed by manufacturers. However, trace drawings can be obtained and used, although they are not as precise as CAD data. The study results shown here were based on data obtained by reading the coordinates from trace drawings of 100 models of Japanese cars. Furthermore, given that some prototypes of PV-powered vehicles have their rear windows covered with PV cells coordinate data was acquired for the sum of sets of roofs with and without rear windows.

Next, the parameters that described the curves were extracted, and their distribution and the mutual relationships between individual parameters were used to estimate the population statistically. Samples were then randomly extracted from the estimated population, and differential geometry methods were used to perform various analyses[4].

3.2.3 Results of Investigation of PV Installation Capacity

Fig. 3.2-1 shows a histogram of the roof area that can be covered with PV cells and a histogram of the curved surface compensation coefficient based on the relationship between the roof area and the curvature. In determining the coverability, for expedience, areas with an average curvature greater than a spherical surface with a curvature radius of 1 m unsuitable for installation were considered. It is also considered that areas with steep angles where the annual power generation would be less than 50% of that on a horizontal surface as unsuitable for installation. The curved surface compensation coefficient is the ratio of the insolation received divided by the insolation received by a flat surface with the same number of cells over a year. It is 1 when PV cells are placed on a flat surface and decreases as the curvature of the surface increases. It indicates what percentage of adequate insolation PV cells receive compared to those placed on a flat surface[15,16].



Histogram of area that can be covered with PV cells (m^2)
(Excluding any areas where the buckling compression stress on the cells would be excessive)

Histogram of curved surface compensation coefficient

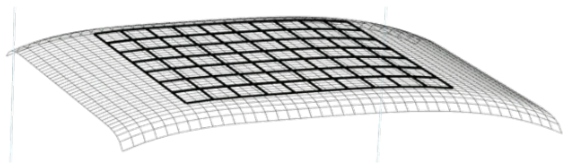
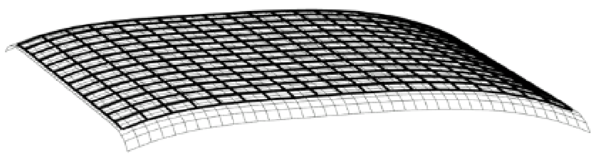
Fig. 3.2-1 Histogram of PV-mountable area and histogram of curved surface compensation coefficient

When estimated using the median value, the roof and PV-mountable areas would be 2 m^2 and 1.9 m^2, respectively[14].

In reality, whether or not the areas with high curvature can be covered depends on the cell's surface area. Furthermore, the widths of car roofs are not always a multiple of the widths of PV cells, and gaps between cells become dead areas. Such constraints were also taken into consideration. For example, Table 3.2-1 shows a comparison of the results between using standard size (166 mm x 166 mm) crystalline silicon cells and using their quarter-cut variants.

Using quarter-cut cells makes it possible to install cells in areas with greater curvature and increases the number of strings, reducing the mismatching loss due to uneven solar irradiation on a curved surface. However, at the same time, it is essential to note that there are more dead areas between cells, so the coverage ratio does not match the coverage capacity, and increasing the number of cuts does not necessarily increase the amount of power generated.

Table 3.2-1 Coverage design and power generation performance of different sizes of cells installed on a standard curved vehicle roof

	
166mm ×166 mm: standard size (full-size)	166mm ×166 mm: quarter-cut
Two strings	Eight strings
Cell coverage rate: 83.3%	Cell coverage rate: 90.8%
Annual generation compared to the horizontal surface: 82.1%	Annual generation compared to the horizontal surface: 87.4%

The shapes and sizes of cells and how they are arranged (how they are wired) on a given vehicle body curve significantly influence the power generation performance. In the future, vehicle bodies designed to be more aerodynamic to improve electric fuel economy are expected to become more widespread. Even in this scenario, design methods that produce optimal cell shapes and arrangements (such as using interactive design sequences instead of simple optimisation methods) will be a pressing issue.

3.2.4 Issues and Prospects (Statistical Assessment of Vehicle Body Shapes and Their Impact on Power Generation)

- Coverage of vehicle body areas other than roofs (three-dimensional curved surfaces)
  - ➢ The most effective way to increase the capacity of vehicle-mounted PV cells in the future will be to install them in areas other than the roof. Except for bodies like double bubble car design, generally speaking, vehicle roofs are simple convex surfaces without depressions, so they are easy to handle using differential geometry. On the other hand, when installing PV cells on engine hoods, for example, there will be hidden surfaces, such as shadows cast by windscreens, so these surfaces are not as easy to work with. If the sides of a vehicle are covered, the amount of light reflected by road surfaces will need to be modeled accurately. These present difficulties, but the calculation is not impossible, and there is a high possibility for quantitative modelling.
- Optimal arrangement and optimal string subdivision problems
  - ➢ Although it is impossible to avoid mismatching loss caused by the vehicle body shape, the effects of partial shading and dynamic shading, as shown in Fig. 3.1-1, vary significantly depending on whether the vehicle is parked or moving, the depth of the vehicle body's curved surfaces, and how these factors are weighted. As a result, the optimal string structure will also vary. In other words, an optimal division method that considers the balancing of these elements must be developed. As of the present, no feasible solutions have been found.
- Curved surface module testing Method
  - ➢ PV module testing methods developed for flat surfaces cannot be used for curved surface

PV modules. A global consensus must be reached regarding various testing methods for curved surface modules (including methods for adjusting the test results of conventional methods). For this issue, Japan is also taking the lead in deliberations and alignment of test results (round-robin testing)[9].

3.3 Curved Surface Module Verification

Vehicle bodies are made up of three-dimensional curved surfaces to reduce air resistance and for aesthetic reasons, so when vehicle bodies are covered with PV cells, the cells are subjected to bending stress. If this stress exceeds the breaking strength of the cells, the cells will crack, leading to a decrease in power generation performance and reliability. New measures will be needed to reduce such breakage risk in automotive applications. Therefore, design methods for PV modules to be used on three-dimensional curved surfaces were deliberated, and a prototype of a curved surface module was made[17].

3.3.1 Prototyping of the Curved Surface Module

Various PV cells are in commercial use or under development, but single-crystalline silicon PV cells were the most widely used for the prototype. Single-crystalline silicon is a brittle material and tends to fracture easily. First, a bending test was performed to determine the breaking strength (the amount of stress that causes breakage). Next, the simulation (finite element method analysis) to estimate stress on the cells when pressed against a curved surface was performed. At this point, cell shapes and sizes were changed, and how they related to cell stress was investigated. Based on the results, the cell shapes with minimal breakage risk for any given curved surface were estimated.

Fig. 3.3-1 shows photographs of curved surface modules designed and prototyped using this method, along with EL inspection images. The 50 cm x 50 cm square of a sphere with a 1 m and 1.5 m radius was cut out to create three-dimensional curved surfaces. The curvature radii of typical passenger vehicle bodies are estimated to be between 1 m and 3 m, but for verification, degrees of curvature at the more pronounced end of this range were set intentionally. Roughly 3-inch square cells were used for these curved surfaces (these cells had roughly 1/4 of the area of the cells used in typical PV modules). This shape and size have a low level of breakage risk, as determined using the design above method. As a result, as the EL inspection images show, curved surface modules without any cell cracks were prototyped. Cell cracking occurred during the prototype's lamination process with the 1 m curvature radius, but this issue was eliminated by adjusting heating temperature conditions.

In the above way, it was confirmed that it is possible to manufacture curved surface modules with low levels of cell breakage risk by using the design methods based on bend testing and stress analysis for the cells that are used. It appears likely that the same methods can be applied as a general rule even when the type of cells is changed. For practical use, the reliability evaluation criteria below must also be satisfied, and the durability necessary for vehicle mounting must be ensured based on reliability improvement technologies developed through conventional stationary PV modules.

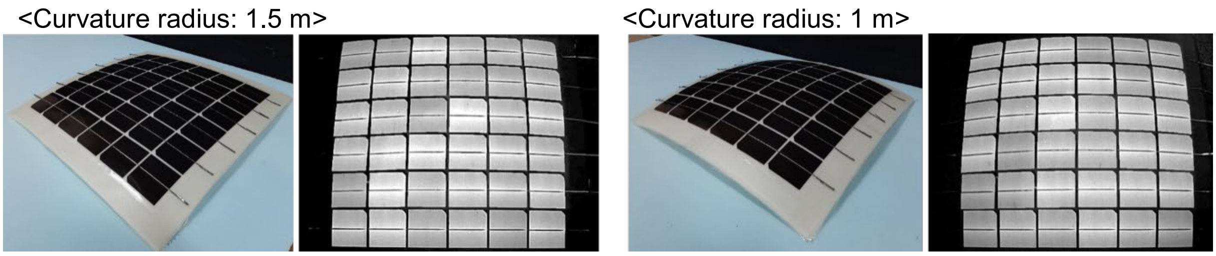


Fig. 3.3-1 Photographs of prototyped three-dimensional curved surface modules and EL inspection images[17]

3.3.2 Power Generation Performance of Prototyped Curved Surface Modules

Power generation performance testing was performed outdoors using one of the prototyped curved surface modules (the prototype with the 1.5 m curvature radius)[18].

As Fig. 3.3-2 shows, the curved surface module was horizontally placed alongside a flat module with the same cell arrangement, and their power generation amounts were measured on a clear day (in April).

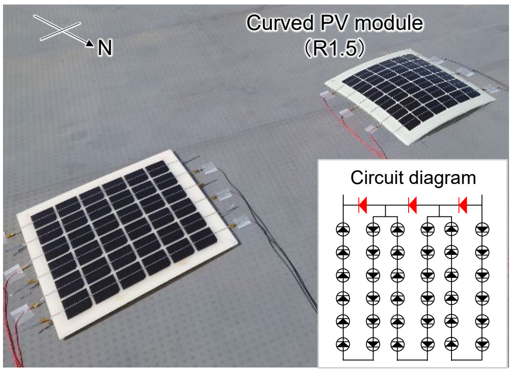


Fig. 3.3-2 Testing the power generation performance of the three-dimensional curved surface module[18]

Fig. 3.3-3 shows the power generation results on a clear day in April. The ratio of the power generation (maximum output) of the curved surface module to that of the flat module shows that the amount of power generated by the curved surface module was relatively lower in the morning and the evening when direct sunlight was slanted. This is due to self-shading, as discussed in 3.2. In other words, there were differences in the amount of solar irradiation received by each cell in the curved surface module, and power generation was limited by the current of cells with low solar irradiation. These results confirmed the current mismatching loss due to uneven solar irradiation of the curved surface, as discussed in 3.2. When applying PV cells to curved surfaces, this loss must be assessed, and measures must be taken to mitigate it (such as optimising the number of strings and bypass diodes).

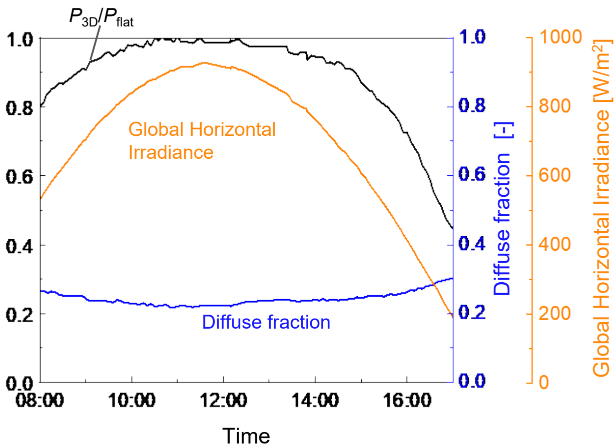


Fig. 3.3-3 Results of power generation performance testing of the three-dimensional curved surface module (on clear days in April)[18]

3.3.3 Changes in Temperature When Installed on Vehicle Roof

For vehicles, special attention must also be paid to PV module temperature changes. A driving speed of 50 km/h is roughly equivalent to 14 m/s wind speed, so the range of wind speeds and the rate of change over time for vehicle-mounted modules are greater than those for conventional modules in fixed position. Moreover, the heat transfer coefficient of natural convection when parked dramatically differs from that of convection when driving, possibly leading to significant temperature changes in the module.

To investigate this impact, a PV module (flexible-type) was installed on the roof of an actual car (a sedan type) as shown in Fig. 3.3-4, and temperature changes were measured[19].

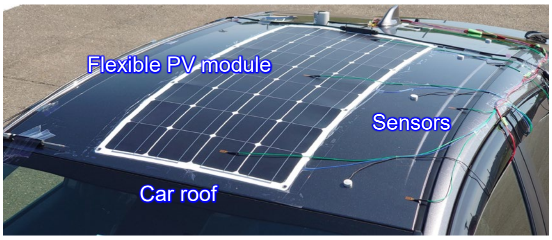


Fig. 3.3-4 PV module attached to a car roof [19]

On a clear day in October, this vehicle was parked in a nearly shadow-free parking lot for three hours (from 10:30 to 13:30) and then driven for approximately 90 minutes on general roads. Temperature data was taken by the thermocouples attached to the module's surface and back. The measured data is shown in Fig. 3.3-5. The module temperature rose to almost 65°C during parking, but convection promoted heat transfer when the vehicle began driving, and the temperature fell rapidly. The vehicle stopped at irregular times due to traffic conditions, such as red lights, and each time it stopped, the module temperature rose (primarily the surface temperature). When the vehicle started driving, the temperature fell again. The maximum temperature change rate was approximately 8 °C/min, and the average was approximately 2.5 °C/min. These were both greater than the maximum rate of change of temperature (100°C/h) for temperature cycle testing specified in IEC 61730-2 "Photovoltaic (PV) module safety qualification - Part 2: Requirements for testing," indicating the need for careful attention in reliability testing. This test also demonstrated that convection heat transfer rates vary depending on the shape and position of the vehicle's roof.

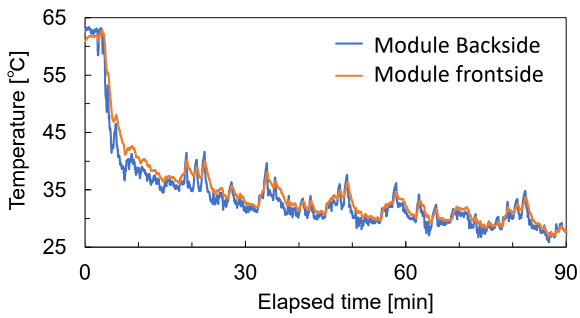


Fig. 3.3-5 Changes in Temperature of PV Module Attached to Vehicle Roof (on Clear Days in October)[19]

3.3.4 Issues and Prospects

PV modules installed on vehicle roofs have been rolled out commercially in vehicles such as the Prius PHEV, and there have not been any reports of reliability issues. Glass has been used to cover the surfaces of the modules, and the curvatures are slight. In the future, PV cells may be installed on parts of vehicles other than the roof, as indicated in 3.2, and the use of resin may also be considered from perspectives like weight reduction, impact absorption, and shape compatibility. Requirements and characteristics will need to be specified for each part of vehicle bodies (roof, doors, bonnet, windscreens, etc.), and corresponding module materials, structures, and low-cost mass-production technologies will need to be established. Furthermore, it will be necessary to estimate the impact of vehicle specific environments and specifications on the long-term reliability of modules and associated devices. Additionally, design and textural qualities are more emphasized for vehicle-mounted PV modules than for conventional PV modules, so technologies such as colouring to heighten PV modules' decorative appeal will need to be addressed.

3.4 Comparison of Standards for Terrestrial PV and Vehicle-mounted PV

Vehicle-mounted PVs are exposed to operating environments different from the regular PVs installed on building roofs or on the ground, so the expected requirements for durability and reliability differ. In this section, reliability assessment items to be met by vehicle-mounted PVs, compared to terrestrial PV assessment items, are investigated, and assessment items specific to vehicle-mounted PVs are qualified[20].

3.4.1 Standards in Comparison

Given that vehicle-mounted PVs have aspects of both terrestrial PVs and automotive components (electrical and electronic equipments, glass), the following international and Japanese standards (ISO, IEC, JIS, and JASO), which stipulate reliability evaluation tests assuming their operating environments, were investigated.

For details regarding each standard, please refer to the respective standard documents.

Standards for terrestrial PV module

- **IEC 61730-2:2016,** Photovoltaic (PV) module safety qualification – Part 2: Requirements for testing
  (**JIS C 61730-2:2020,** Photovoltaic (PV) module safety qualification – Part 2: Requirements for testing)
- **IEC 61215-2:2016**, Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures
  (**JIS C 61215-2:2020**, Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures)
- **IEC 61701:2020**, Photovoltaic (PV) modules – Salt mist corrosion testing
- **IEC 62716:2013**, Photovoltaic (PV) modules – Ammonia corrosion testing

Standards for automotive component

- **ISO 16750-2:2012**, Road vehicles – Environmental conditions and testing for electrical and electronic equipment – Part 2: Electrical loads
  (**JASO D 014-2:2014**, Automotive parts - Environmental conditions and testing for electrical and electronic equipment - Part 2: Electrical loads)
- **ISO 16750-3:2012**, Road vehicles – Environmental conditions and testing for electrical and electronic equipment – Part 3: Mechanical loads
  (**JASO D 014-3:2014**, Automotive parts - Environmental conditions and testing for electrical and electronic equipment - Part 3: Mechanical loads)
- **ISO 16750-4:2010**, Road vehicles – Environmental conditions and testing for electrical and electronic equipment – Part 4: Climatic loads
  (**JASO D 014-4:2014**, Automotive parts - Environmental conditions and testing for electrical and electronic equipment - Part 4: Climatic loads)
- **ISO 16750-5:2010**, Road vehicles – Environmental conditions and testing for electrical and electronic equipment – Part 5: Chemical loads

(**JASO D 014-5:2014**, Automotive parts - Environmental conditions and testing for electrical and electronic equipment - Part 5: Chemical loads)

- **JASO D 902:2012**, Automotive parts – Electronic equipment – Durability testing methods
- **JIS R 3212:2015**, Test methods of safety glazing materials for road vehicles

3.4.2 Comparison Results of Standards for Terrestrial PV and Automotive Components

Table 3.4-1 categorises the reliability assessment items for terrestrial PV and automotive components into mechanical, climatic, electrical, and chemical loads. This section only contains test items intended for maintaining essential performance. Items related to the safety protection of passengers and pedestrians against fire, electrical shocks caused by malfunction, collision, etc., are not included. The table contains the test numbers or section numbers of individual reliability tests stipulated in the standards. Tests to which the entire standard applies are marked with "○". The reliability assessment items that only apply to terrestrial PV, that only apply to automotive components, and that apply to both are colored green, red, and blue, respectively.

Table 3.4-1 Reliability assessment items for terrestrial PV and automotive components

Category	Reliability assessment items	Terrestrial PV				Automobile components					
		IEC 61730	IEC 61215	IEC 61701	IEC 62716	ISO 16750				JASO D902	JIS R 3212
						-2	-3	-4	-5		
Mechanical	Surface strength	MST 12					4.4				
	Hail / Steel ball falling		MQT 17								5.4
	Static mechanical load	MST 34	MQT 16								
	Vibration						4.1			6.4	
	Mechanical shock						4.2				
	Gravel bombardment						4.5				
Climatic	Steady-state temperature	MST 37, 55, 56						5.1			5.19
	Dump heat	MST 53	MQT 13					5.7		6.3	5.10
	Thermal cycling	MST 51	MQT 11					5.3.1			
	Humid heat cycle	MST 52	MQT 12					5.6			
	Solar radiation	MST 54	MQT 10					5.9			5.17
	Outdoor exposure		MQT 08								
	Salt corrosion			○				5.5			
	Ammonia corrosion				○						
	Thermal shock							5.2, 5.4 5.3.2		6.2	
	Mixed gas corrosion							5.8			
Electrical	Hot-spot endurance	MST 22	MQT 09								
	EMC					4.13					
Chemical									○		5.15

Surface strength, hail/ steel ball falling, thermal load (steady-state temperature, dump heat, thermal cycling, humid heat cycle), solar radiation , and salt corrosion are stipulated both for terrestrial PV and automotive components. Although detailed deliberation is required regarding which standard conditions are suitable for testing vehicle-mounted PV. For thermal load, as Tables 3.4-2 to 3.4-5 show, terrestrial PV seems to be tested under generally more harsh conditions (in the table, only the standards with the most severe conditions are indicated for terrestrial PVs and automobile components). The test conditions with more severe value are highlighted in red in the tables.

Table 3.4-2 Steady-state temperature testing

Standard	Terrestrial PVs IEC 61730-2 (MST 55, 56)	Automotive components ISO 16750-4 (5.1)
Lower temperature	-40℃	-40℃
Duration at lower temperature	48 h	24 h
Higher temperature	105℃	85℃
Duration at the higher temperature	200 h	96 h

Table 3.4-3 Dump heat testing

Standard	Terrestrial PVs IEC 61730-2 (MST 53)	Automotive components ISO 16750-4 (5.7)
Temperature	85±2℃	85±2℃
Relative humidity	85±5℃	85±5℃
Duration	1000 h	1344 h

Table 3.4-4 Thermal cycling testing

Standard	Terrestrial PVs IEC 61730-2 (MST 51)	Automotive components ISO 16750-4 (5.3.1)
Minimum temperature, T_{min}	-40℃	-40℃
Maximum temperature, T_{max}	85℃	80℃
Temperature changing rate between T_{min} and T_{max}	Max. 1.67℃/min	Max. 1℃/min
Number of cycles	200	30

Table 3.4-5 Humid heat cycle (condensation) testing

Standard	Terrestrial PVs ISO 16730-2 (MST 52)	Automotive components ISO 16750-4 (5.6.3)
Minimum temperature, T_{min}	-40℃	25℃
Maximum temperature, T_{max}	85℃	80℃
Relative humidity @ T_{max}	85±5%	≧95%
Number of cycles	10	5

On the other hand, vibration (vibration induced in the vehicle body by driving on rough roads), mechanical shock (shock loads from slamming doors or driving over curbs at high speeds, etc.), gravel shock, thermal shock (temperature changes within extremely short periods due to sudden speed changes or splashing water, etc.), mixed gas flow corrosion, electromagnetic compatibility (EMC), and chemical load tests are only stipulated for automotive components, so these would be reliability assessment items specific to vehicle-mounted PVs. In particular, environmental conditions that involve repeated loads of which magnitude changes with extremely rapid rates, such as vibration, mechanical shock, and thermal shock, are not considered for terrestrial PVs. This shows vehicle-mounted PV modules are exposed to more harsh environments than terrestrial PVs. For example, in the mechanical shock testing stipulated in ISO 16750-3, a sinusoidal pulse with a peak acceleration of 500 m/s^2 is applied within 6 ms (in the case of devices attached to the body). In the thermal shock testing stipulated in JASO D 902, the temperature changes from -40°C to 85°C within five minutes. This is more than 15 times the rate of temperature change in the thermal cycling testing regulated in Table 3.4-4.

3.4.3 Future Outlook

The reliability assessment items to be met by vehicle-mounted PVs were clarified. In the future works, in order to formulate reasonable testing scheme that take into consideration practical lifetimes, implementation costs, and other factors, it will be planned to collaborate with related organisations, automotive manufacturers, and PV cell manufacturers in discussions and considerations regarding the testing items, prioritisation, testing conditions (number of samples, strictness, etc.), and acceptance criteria. Furthermore, there are plans to investigate safety design requirements for modules, such as protection of passengers and pedestrians in the event of collisions, measures against fires and electric shocks, and the impact of material toxicity.

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Chapter 4: Conclusions

There are various movements, both in Japan and overseas, toward the realisation of PV-powered vehicles. This report provided an overview of trends related to PV-powered vehicles and presented the results of demonstration driving of PV-powered vehicles in Japan equipped with ultra-high efficiency PV that has a rated output of around 1 kW. It also summarised the status of researches related to identifying the characteristics of solar irradiation and power generation achievable by vehicle-mounted PV, as well as developing measures of evaluating the performance required for PV. These researches will form the foundation of efforts to fully realise PV-powered vehicles.

Below is an overview of the findings presented in each chapter, along with the future outlook, issues, and initiatives.

4.1 Findings

4.1.1 Trends in PV-powered vehicles

PV was initially used in passenger vehicles for ventilating the interior of the vehicle, but now the energy generated has come to be used for the vehicle's drive (to power vehicle driving). In recent years, not only has the output of PV been increased, but the application of PV has extended to commercial vehicles as well.

- The Prius PHEV launched in 2017 is the world's first mass-produced PV-powered vehicle that uses the PV generated power for driving. Although it could not drive solely on PV, there have since been announcements and market introductions of PV-powered vehicles with outputs of roughly 200 W of power for driving.
- In order to supply as much driving power as possible from PV, efforts have begun to equip automobiles (passenger vehicles) with PV power outputs on the order of 1 kW by covering the roof and bonnet with PV that has efficiency rates of over 30%. In Japan, NEDO has developed demonstration vehicles and has performed demonstration driving since 2019. In Europe, venture companies have been working toward an early market release.
- In addition to passenger vehicle initiatives, in recent years, onboard PV have begun to appear in commercial vehicles in Europe and the U.S.. In large vehicles such as trucks and trailers, the generated PV power is used for refrigeration. While in smaller vehicles, similar to passenger vehicles, efforts are being made to use PV power for driving.

4.1.2 Demonstration Driving of PV-powered Vehicles

The effectiveness of PV systems varies depending on the PV output, vehicle driving patterns, driving and parking environments, and vehicle models. Though trials are still being carried out, and various results and issues will be discovered in the future, based on the results that have been produced so far, the following findings have been made.

(1) Demonstration driving of plug-in hybrid vehicle (PV cell output: 860 W)

- For a driving pattern in which the demonstration vehicle was driven for 35 km in the morning and afternoon, primarily on expressways, a vehicle driving energy consumption rate was measured to be roughly 10.1 km/kWh (primarily performed in Nagoya City).

- Vehicle-mounted PV charged batteries during daytime parking, supplementing the power consumed by driving in the morning. The amount of solar power generated on the day of measurement in June 2020 (under clear skies) was roughly 4 kWh/day. The trial confirmed that this would be sufficient to drive approximately 30 km/day.
- Furthermore, based on measurement performed in September 2021, the mutual relationship between the amount of solar irradiation as measured by pyranometers attached to the vehicle and the cruising distance was examined. It was determined that the driveable distance from PV power and the amount of solar irradiation per day were proportional, and the constant was 5.9 km/(kWh/m^2/day). While seasonal differences in power consumption rates must be taken into consideration, Tokyo, for example, receives approximately 1,200 kWh/m^2 of solar irradiation per year. A vehicle with an 860 W PV would therefore, theoretically, be able to drive approximately 7,080 km per year.

(2) Demonstration driving of battery electric vehicle (PV cell output: 1,150 W)

- Given the actual driving energy consumption rate determined by driving on public roads (roughly 6 km/kWh) and the estimated power generation amount based on a solar irradiation database (for Yokohama City), the driveable distance from PV power is 7,100 km per year. Due to seasonal variations in the amount of power generation and electricity consumption, the driveable distance from PV power is roughly half as much in winter as it is in summer.
- Assuming a driving pattern consisting of weekday commuting, charging frequencies were calculated based on solar power generation amounts, power consumption rates, and driveable distances determined through trials. It was found that charging would be unnecessary if the commuting distance is 10 km one way, and the annual charging frequency could be cut by roughly 52% if the commuting distance is 25 km one way. In some cases, the battery state of charge (SOC) could return to 100% during non-driving daytime on weekends. This indicates that there is an excess of the PV power generated, and attention should be given to how to optimise PV power generation output and power uses (such as supplying electricity for external use).
- With respect to the shade that falls on the vehicle when driving, to deal with shadows that move in front-rear direction, which are expected to occur frequently, cells could be arranged in series horizontally across the vehicle (perpendicular to the direction of driving) to maintain module voltage, reducing the loss in power generation caused by a decline in module current.
- In conditions where the vehicle moves between sunlight and shade, the MPPT control initial search voltage could be raised to improve the MPPT control response. When the MPPT voltage is roughly 38 V, setting the initial search voltage between 20 and 35 V would raise the MPPT achievement rate to 97% or higher.

4.1.3 Research for Realisation of PV-Powered Vehicles

There are various differences between the vehicle-mounted PV and conventional terrestrial PV. Researches have been taken to assess these differences from the perspectives of the impact of shade, flatness/curvature, and environmental testing, and to address the issues presented by these differences.

- The amount of power that can be generated by PV mounted on a vehicle's roof is influenced by the amount of solar irradiation on the vehicle roof -- that is, the distribution of positions and angles of elevation, etc., of buildings and other obstructions that cast shadows on the vehicle when it is driving. There is little difference in the impact of these factors depending on the geographical location. Instead, the sunlight environment of driving areas has a major impact. For example, the amount of solar irradiation on the roof of a vehicle driven through a residential area is roughly 70% of the amount of solar irradiation on a fixed, horizontal surface.
- The shapes and sizes of cells on the curved surfaces of automobile roofs, and how they are arranged (or wired), have major impacts on the power generation performance. Assuming a standard passenger vehicle's curved roof surface, 83.3% of the roof surface area can be covered with 166 mm square crystalline silicon cells, and the amount of power that can be generated per year is estimated to be 82.1% compared to a flat surface. Furthermore, with the cells' quarter-cut variants, the coverage rate increases to 90.8%, and the annual power generation is raised to 87.4% compared to a flat surface. In the future, it will be important to take aerodynamics into consideration and develop design methods for determining optimal cell shapes and arrangements.
- When covering a vehicle's roof, which is a three-dimensional curved surface, with PV cells, bending stress acts on the PV cells. However, design methods based on bend testing and stress analysis of the cells can make it possible to produce curved surface modules with low cell breakage risk. However, shadows cast by the module itself in the morning or evening, along with uneven solar irradiation, can cause current mismatching loss, so measures must be taken to assess and reduce the loss. Furthermore, temperature change cycles caused by repeatedly switching between moving and stopping can result in temperature change rates greater than those used in PV module temperature cycle testing, so further attention must be given to this issue.
- Looking at reliability evaluation criteria for conventional terrestrial PV and automotive components, although some tests, such as surface strength, hail/steel ball drop, and thermal load testing, are stipulated for both, there are also tests that are only stipulated for automotive components, such as vibration, mechanical shock, thermal shock, and chemical load testing. Specific evaluation criteria for vehicle-mounted PV must be identified, and efforts must be carried out with the aim of developing reasonable testing methods, etc.

4.2 Future Outlook and Issues

The transport sector will have to play a significant role in achieving carbon neutrality by 2050, and measures by the automotive sector will be of great importance. According to the IEA's Net Zero by 2050[1], energy consumption by the transport sector in 2050 is to be cut by more than 20% compared to the 2020 levels, and 45% of that energy is to be electrical. What's more, roughly 60% of the energy consumed in 2050 will be consumed by the automotive sector. To achieve the goals set forth in Net Zero by 2050, almost all vehicles sold in 2050 will have to be electric vehicles, and by 2030, the cumulative number of electric vehicles should exceed 3.5 million[2]. IRENA[3] states that electricity must account for 49% of the energy consumption, and the adoption number of electric vehicles should reach 1.89 million in the transport sector by 2050. Furthermore, the U.S. DOE forecasts that the capacity of renewable energy (decarbonised) power generation facilities will reach 3 TW (including 1.6 TW from solar power) in 2050, and the transport sector will account for roughly 20% of the electricity usage (supply)[4].

Although it is not clear how PV-powered vehicles are positioned within these forecasts, moves toward the realisation of PV-powered vehicles have already begun in Japan, Europe, and the U.S[5,6,7]. PV-powered vehicles help reduce CO_2 emissions by using solar-generated power to directly supply the electricity used by vehicle motors. Furthermore, they can reduce the charging frequency, which has been one of the obstacles to the widespread adoption of electric vehicles. This provides users with greater convenience.

Through demonstration driving on public road and various technology development, the benefits and challenges of PV-powered vehicles have been confirmed and verified in the actual field. This development has provided a wealth of insights, but initiatives such as those shown in Table 4.2-1 must be further accelerated to achieve full-scale commercialisation of PV-powered vehicles.

To achieve greater market penetration, it will be important to showcase and expand the benefits these vehicles provide to users, so further verification through trials will be necessary. It will also be important for PV-powered vehicles not only to be widely adopted by individual users, but also to be actively used by municipal governments and to be positioned in policies by the national government. In addition to environmental measures such as those aimed at reducing CO_2 emissions, in recent years, there has been a growing focus on resilience, such as disaster-prevention measures, and expectations are high for the benefits and contributions to be made by PV-powered vehicles. Automobile applications that involve PV power will also become more diverse in order to expand the range of users.

From the standpoint of PV power generation performance, the efficiency of PV systems must be increased and the generated power usage efficiency must be improved by effectively utilising surplus generated electricity. It will also be important to develop system designs that maintain high levels of usage efficiency. Also of importance will be the maximisation of PV power generation output when PV cells are integrated as components into vehicle bodies (generating the maximum amount of power from a given amount of insolation) and the selection of materials, such as surface covering materials and backing materials, taking into consideration of vehicle weight and safety. Aesthetic design that matches user tastes will also be important, and this must be taken into consideration with respect to power generation performance and material selection. It will also be vital to standardise performance evaluation and testing methods in order to maintain a safe and stable supply of products that meet such performance and other requirements

Table 4-2-1 Challenges and initiatives aimed at the full-scale realisation of PV-powered vehicles

Verification of the benefits of PV-powered vehicles	- Quantification of driveable distance from PV power - Measurement and analysis of benefits based on driving patterns and environments, and identification of features (CO_2 emissions reduction and charging frequency reduction) - Consideration of measures for improving effectiveness - Proposals of new value and benefits (resilience, etc.) - Diversification of PV applications (lightweight passenger vehicles, compact commercial vehicles, large trucks and trailers, buses, etc.)
Improvement of PV power usage efficiency	- Maximisation of efficiency of usage of PV power for drive power (reduction of electrical loss in circuits and systems between PV and drive batteries) - Effective use of PV power when batteries are fully charged (SOC=100%) (provision of power for use externally: V2X) - Optimisation of system designs, including PV power generation output
Consideration of methods of integrating PV cells and modules into vehicle bodies	- Optimisation of PV cell coverage of vehicle roofs, etc. (maximisation of acquired insolation, support for use on three-dimensional surfaces, such as resistance to bending stress) - Optimisation of cell shapes, arrangements, and string formations - Optimisation of module structure and materials, and improvement of aesthetic designs
Standardisation of evaluation and testing methods of power generation performance, safety, etc.	- Standardisation of energy ratings - Methods of measuring insolation, power generation, etc. - Methods of testing electrical and mechanical performance of curved surface modules - Reliability evaluation criteria, and evaluation and testing methods for PV cells as automotive components

The current PV power generation market is being dominated by other countries, such as China. In the automotive sector, as well, electric vehicle development initiatives are intensifying around the world, and competition is growing fierce.

Japan is currently leading IEC discussions regarding the standardisation of energy ratings for vehicle-mounted PV and leading IEA PVPS discussions regarding the added value and technical requirements of PV-powered vehicles. Japan can use these opportunities to share the efforts to the world and enhance its presence.

Initiatives related to PV-powered vehicles are still in their infancy, but it is hoped that companies and stakeholders involved in the development and manufacture of PV and electric vehicles will work together as one, expanding the PV-powered vehicle market and thereby stimulating related industries in Japan.

4.3 Future Initiatives

To address these issues outlined above, we will continue to conduct researches on PV-powered vehicles.

We will continue to identify issues from demonstration driving, consider solutions, and verify quantitative effects of the solutions, while collecting useful information from the twin perspectives of PV power generation and automobiles. We will also continue to engage in a range of technical development efforts that may lead to international contribution and standardisation, thereby contributing the widespread global adoption of PV-powered vehicles.

Furthermore, NEDO is developing PV technologies envisioned for use in automobiles and other transport vehicles. The PV cells currently used in automobiles available on the market are crystalline silicon PV cells, but ultra-high-efficiency PV cells with power generation efficiency rates of 35% or more can produce high levels of output within limited installation spaces, and perovskite/silicon tandem PV cells are expected to achieve power generation efficiency rates of 30% or more while being low-cost and offering exceptional conformability to curved surfaces. These PV cells have tremendous potential for use in means of transport, and expectations are high for these Japanese technologies to come to the forefront around the world.

In the future, while keeping our eyes set on the commercialisation of these PV cells, we will carry out various initiatives that contribute to the full-fledged practical application of PV-powered vehicles and the revitalisation of related domestic industries.

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