State-of-the-Art and Expected Benefits of PV-Powered Vehicles

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Executive Summary

The market for PV systems has been rapidly expanding with significant penetration in grid-connected markets in an increasing number of countries, connected to both the distributed as well as the central transmission network. This strong PV market expansion has been contributing to savings in fossil fuel consumption and mitigating environmental impacts in residential, commercial, industrial and power sectors. In contrast, the PV market in the transport sector is still small. However, there is a huge potential.

In the transport sector, battery and plug-in hybrid electric vehicles are being adopted globally as a solution to mitigate CO_2 emissions. In line with this, vehicle emissions targets have been proposed and adopted by many countries and policy bodies around the world with goals for the adoption and use of electric vehicles in the near future. With widespread electrification of transportation, PV generated electricity and other renewable energy sources are needed to leverage the EV adoption into even more significant CO_2 emissions reductions. The distributed nature of PV electricity generation offers new opportunities for charging battery electric vehicles.

Options for low-carbon charging of electric vehicles include charging from the existing grid network with PV or other sustainable electricity sources, charging from a dedicated charge point with local PV electricity generation, or directly and independently with on-board PV (PV-powered vehicle).

In order to contribute to reducing the CO_2 emissions of the transport sector and to enhance PV market expansions, IEA PVPS Task 17 is aiming to clarify the potential of the utilization of PV in transport and to propose how to proceed towards realising the concepts. Task 17’s scope includes various PV-powered vehicles such as passenger vehicles, light commercial vehicles, heavy duty vehicles and other vehicles, as well as PV applications for electric systems and infrastructures, such as charging infrastructure with PV, battery and other power management systems.

Among these options, this report has focused on PV-powered vehicles, with on-board integrated PV systems, that can run anywhere without or with less dependency on grid electricity. These vehicles offer more than just low emissions transport but also options of convenience and autonomy. The market introduction of PV-powered vehicles can be important for the uptake of electric transport and create opportunities for other PV applications in the transport sector, as well.

This report is the first technical report of Task 17, as an interim report, and presents on the recent trends in PV-powered vehicles including PV technologies, expected benefits of PV-powered vehicles, estimates of solar irradiance on vehicles, and next steps for realising PV-powered vehicles in the market.

A. Recent trends in PV-powered vehicles

In recent years, multiple projects, consortia and companies have been aiming at delivering PV-powered vehicles, especially passenger vehicles. Considering the direct usage of PV electricity for vehicles, the available area for PV modules is limited. However, even in a limited area PV will be able to supply electricity to the battery of the vehicle.

As pioneer manufacturers of PV-powered vehicles in Europe, Sono Motors and Lightyear are developing PV-powered passenger vehicles equipped with crystalline Si solar cells, and their vehicles will be likely coming to the market (see Figs. A-1 and A-2). “Sion”, by Sono Motors, has lightweight PV modules at least 20% lighter than comparable metal body parts, which can generate 1 208 Wp. Sono Motors estimates a range of 5 800 km/year using only solar energy and up to 34 km/day (in Munich). “Lightyear One”, by Lightyear, has been designed to be very light, with high performance materials. PV modules on 5 m² and 215 Wp/m² may provide up to 70 km/day. Additionally, CEA-INES developed a prototype vehicle equipped with 1,3 m² crystalline Si PV modules.

In Japan, two major car manufacturers, Toyota Motor Corporation (Toyota) and Nissan Motor Corporation (Nissan), engineered prototypes of PV-powered passenger vehicles using high-efficiency III-V multijunction solar cells,

supported by NEDO, and started testing. PV capacity of Toyota's PV-powered vehicle, Prius-HEV, is 860 Wp and that of Nissan's PV-powered vehicle, e-NV200, is 1 150 Wp (see Figs. A-3 and A-4). It is noted that both vehicles are commercial passenger vehicles implying that the III-V multijunction solar cells are capable of being mounted on normal passenger vehicles without sacrificing elegant body shapes.

Fig. A-1 Sion from Sono Motors
(https://sonomotors.com/en/sion/)

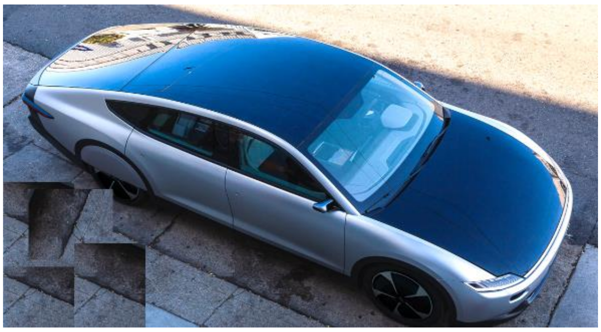


Fig. A-2 Lightyear One
(https://lightyear.one/lightyear-one)

Fig. A-3 PV-powered Prius-HEV (Toyota)
(https://www.nedo.go.jp/news/press/AA5_101150.html)

Fig. A-4 PV-powered e-NV200 (Nissan)
(https://www.nedo.go.jp/news/press/AA5_101326.html)

Silicon-based cells are the most common technology for PV-powered vehicles. The modules using silicon-based cells show the best compromise between performances and price with an acceptable level of reliability. The weak point is their lack of flexibility in two-directional bending. III-V multijunction solar cells have also been applied to PV-powered vehicles due to higher power conversion efficiency. The disadvantages are higher price and spectrum mismatching loss compared with crystalline Si solar cells. For reducing such disadvantages, a four-terminal III-V on Si multijunction solar cells has also been demonstrated. Other thin-film solar cells, such as amorphous silicon and chalcogenide, compare unfavourably in efficiency to other photovoltaic technologies. However, they represent the most efficient of the thin-film materials that can be deposited onto glass or metal foil, providing the potential to fabricate curved PV active vehicle body parts directly and perhaps more cheaply. Perovskite cells have the potential of combining high efficiency, low-cost and flexibility, but this technology is not currently manufactured at large scale due to a lack of reliability/durability and, at present, lower efficiency than c-Si based PV at large scale.

From the viewpoint of PV module assembly, there are additional module costs associated with reliable encapsulation of photovoltaic solar cells in curved vehicle body parts. Compared to conventional flat-plate PV modules, these vehicle parts will be manufactured in relatively small volumes for each vehicle design. Curved, flexible and lightweight module technologies with low cost and high reliability are required. The modules will also be subject to vibrational environments that are much more challenging than for standard terrestrial PV modules. The aesthetic appeal of a vehicle will be an important factor in any consumer purchase, so the modules must not only be efficient but also coloured. With well-engineered optical coatings, it is possible to deliver colour with relatively little efficiency loss.

B. Expected benefits of PV-powered vehicles

To a certain extent, PV-powered vehicles replace grid or charging station electricity with on-board PV generated electricity. This offers benefits for users in terms of reduction of CO_2 emissions during driving (in most countries), cost savings, and reduction in the frequency of grid charging, as well as less quantifiable benefits in terms of autonomy and independence. In order to foresee the expected benefits, case studies are included in this report. Modelling and case studies confirm that all PV-powered vehicles will realise the benefits listed above to various levels.

Case studies on PV-powered passenger vehicles

A case study in Japan found that a PV-powered vehicle could produce approximately 220 kg CO_2-eq/year emission reduction in comparison to the same electric vehicle without PV, especially for longer driving distances. However, for shorter driving distances a 1 kW PV system can result in excess PV generation. In order to increase the environmental benefits of PV-powered vehicles, it is necessary to ensure high utilisation of PV electricity. Thereby, many aspects of the PV-powered vehicle need to be considered and optimised; the PV capacity (considering the effective solar irradiation), the vehicle efficiency, and the vehicle battery, including its capacity, efficiency and operating conditions. The Japanese case study also showed that a PV-powered vehicle will have a decreased charging frequency and that in some cases with a shorter driving distance, the PV-powered vehicle will be free from grid electricity charging. This benefit will make the vehicle attractive, even if the expected environmental benefits will only be small.

A case study in the Netherlands showed that even with a relatively low solar irradiation, PV-powered vehicles could make a significant impact on the electricity consumption of electric vehicles. As PV and EVs become more efficient, the impact can increase. It was also shown that driver behaviour, in the form of charging strategies and driving profiles, can have a measurable effect on the benefits of PV-powered vehicles. This may lead to a 60% reduction in charging frequency, which can increase the autonomy and a feeling of security for the EV driver. While CO_2 emissions reduction will depend on the carbon intensity of the local grid, current values for the Netherlands indicate that there can be an effective CO_2 reduction of about 200 kg CO_2-eq/year. Finally, cost savings of up to 164 EUR/year are shown, but are likely to be much higher when commercial EV charging rates would be taken into account, which are currently significantly higher than household electricity prices. It is noted that in order to have the most impact on cost savings and CO_2 emissions, the energy generated by the PV should be utilised to the maximum.

Realising benefits of PV-powered vehicles depends on variables such as driving patterns, available solar irradiance on the vehicle, vehicle efficiency, battery size, PV capacity installed and the utilization of the PV resource. Based on the case studies in Japan and the Netherlands, the expected benefits of PV-powered passenger vehicles in all IEA PVPS Task 17 member countries have been estimated (see D).

Case studies on PV-powered commercial vehicles and trucks

A case study in Germany focused on PV-powered light commercial vehicles. Based on the solar irradiance measurements on specific test routes, it was found that a side-to-roof ratio is about 40% on average. Also, it was estimated that a total energy yield from 1 170 kWh/a (Hamburg, Germany) to 2 210 kWh/a (Rome, Italy) for the modules mounted on the roof and side (2 180 W_p in total). In parallel, a life cycle assessment (LCA) of PV components, assuming production in China and integration in Germany, found that PV-powered vehicles can improve the carbon footprint for the case, based on an average shading factor of 30% and eight years of operation time. The emissions factor of 1 kWh of on-board generated PV electricity is calculated at 0,357 kg CO_2-eq/kWh, and the average grid emissions for the operation time are expected to be 0,435 kg CO_2-eq/kWh. The lower shading factor and the longer operation time are important for realising the environmental benefits.

A case study in Spain discussed the economic feasibility of PV-powered reefer trucks, by integrating PV modules on the roof of refrigerated trucks. ICE engine trucks consume diesel fuel, and the fuel consumption varies with the temperature of refrigeration, ambient temperature, the mass of the pay-load, and the costs of diesel (there are different costs for diesel depending on the fuel being used for driving or for refrigeration). The economic feasibility of PV depends of the use given to the produced PV electricity on-board, and how to substitute fuel and freight load, in addition to the cost and performance of PV. As an example, if the same diesel is used both for motion and refrigeration (0,75 EUR/l), considering that 75% of the time the trucks travel with full load, the best payback time is estimated to be 3,62 years, which seems reasonable from an investment point of view. Based on these conclusions, preliminary concepts for PV-powered heavy-duty vehicles, especially trucks have been indicated.

A case study on PV-powered truck trailers in the Netherlands estimated the PV electricity production on the roof and on the sides of semi-trailers. The vertical installation represents two vertically oriented PV systems attached to the sides of a semi-trailer, and the horizontal installation represents just one roof-based PV system with a similar size as one of the two vertically oriented PV systems. The preliminary studies indicated that the effectiveness of vertical solar panels on trailers, is about 50% of that of roof-based panels. This is highly dependent on the latitude, the route the truck-trailer drives, the locations the truck visits, the surroundings of those locations, the changeability of the weather and the date/time. It will be essential to develop tools and methods to forecast the possible power and energy production during a journey ahead of the actual trip itself.

These case studies have given valuable insights upon which in-depth studies of integrated PV systems for trucks and trailers can build upon. Taking into account the possible use of PV electricity for auxiliary demand, PV integration in trucks and trailers seem close to realisation and will be coming to the market.

Fig. B-1 PV-powered light commercial vehicle
(Photo: Institute for Solar Energy Research Hamelin)

Fig. B-2 PV truck trailer
(Photo: IM Efficiency)

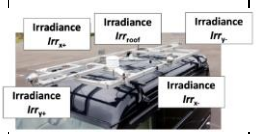
C. Solar irradiance for PV-powered vehicles

In order to promote development and adoption of PV-powered vehicles, it is necessary to understand the effects of the dynamic environment of the vehicle for optimal design of on-board PV systems. The amount of PV electricity generated on-board depends on factors such as available solar irradiance and temperature. The solar irradiance falling on a PV-powered vehicle depends on the specific location and direction during parking and driving. Additionally, the solar irradiance during use is always changing; due to the surrounding environment of the route (buildings, structures or foliage may cause shade or reflect light on the vehicle). Several different methodologies have been developed for measuring the real irradiance falling on vehicles in some organization by: TNO in the Netherlands, ISFH in Germany, the University of Miyazaki in Japan, Bern University of Applied Sciences in Switzerland and UNSW in Australia (see Table C-1).

Although there has not yet been enough data collected to make generalisations on the characteristics of the solar irradiance, each approach led to results and from these, a few tendencies and directions were found.

A preliminary study in Japan, which was conducted at limited locations (Miyazaki city and Sapporo city) and periods of time, resulted in the following observations: shades of buildings, trees, power poles, and the like, cause a drop in solar irradiance in affected locations and sections of the car; larger shades like that of a building may cover an entire surface, such as the vehicle’s roof, or may only partially shade the surface; due to reflections from buildings, the solar irradiance on a vehicle in some locations and sections may exceed the insolation on a roof or rooftop of a building; fluctuations in solar irradiance due to shades and reflections often occur with very short cycles (less than 0,1 seconds). Fluctuations in solar irradiance on vehicle’s roof were observed by measurements in the Netherlands and Germany, as well. Although too few data are available to make generalisations on the characteristics of the solar irradiance on vehicles, it can be stated with some level of confidence that the ratio of solar irradiance on the vehicle’s roof during driving relative to GHI may range from 50% to 90%, e.g. from high-rise sections to urban and open-air sections. A ratio of roof-to-side measured in Miyazaki was from 30% to 50%, 40% on average, which is relatively close to the measured ratio in Germany.

Table C-1 Solar irradiance measurement by some organisations

TNO, Netherlands	ISFH, Germany	Univ. of Miyazaki, Japan	Bern University of Applied Sciences, Switzerland	UNSW, Australia
Four horizontal pyranometers and PV module on roof rack	10 kHz irradiance measurements	Five direction pyranometers on roof rack	Five reference cells on two types of vehicles	Low-cost, autonomous irradiance sensor installed on a large number of vehicles
				
High fidelity irradiance measurements on horizontal plane. Partial and dynamic shading quantified	High fidelity irradiance measurements with high temporal accuracy	High fidelity irradiance measurements in all directions.	High fidelity irradiance measurements in all directions.	Crowdsourced irradiance and driving data under 'real-world' conditions, including parking behaviour

Measurements in Burgdorf, Switzerland found that a vehicle's roof gets around 70% of the irradiance that a flat area of the same extent would receive. This value needs to be confirmed in the months to come as it appears to differ with the position of the sun throughout the year. Also, in this case, the vehicle has very good sun exposure during the whole day. In the case of another vehicle, which is parked in the shade most of the time, the ratio was around 21%. This result shows that where the car is parked will greatly influence the electricity generation of PV on vehicles.

In Australia, two initial vehicle irradiance surveys have been carried out. In the case of a long road trip from Sydney to Canberra, a total of 5,4 kWh/m^2 was estimated to fall on the vehicle during the journey that is estimated to add 30 km of solar range to the vehicle. Long term monitoring of a passenger vehicle during the autumn and winter in Melbourne (and during a period of restricted mobility due to the COVID-19 pandemic) showed that the vehicle was parked 97% of the time and that 80% of the irradiance falling on a passenger vehicle took place while the vehicle was stationary.

In addition to the impact of environmental shading, it was found that at higher latitudes (where there is a relative decrease of the sun's height), the inherent curvature of on-board PV had a negative impact on electricity generation. However, the model-based study in Japan found that both the curve-correction factor and effective solar resource to the vehicle's roof, normalized to GHI, do not show a strong correlation to latitude. They are unlike other typical solar resource parameters, more affected by local meteorological conditions. Also, both the curve-correction factor and the effective solar resource relative to GHI, are strongly influenced by the specific distribution of shading objects.

More irradiance measurements are needed in order to more accurately quantify the possible energy yields and driving distances on solar power throughout the year in specific locations and on specific driving routes. Additionally, once a large data set is acquired, the measured values need to be normalized to standard irradiance levels measured in the past decades in order to eliminate statistical deviances.

Data on solar irradiance acquired by a vehicle is a first step toward the use of PV in automobiles and will provide vital information for evaluating the significance and effect, as well as optimal design, of on-board PV systems.

D. Next steps for realising PV-powered vehicles

This report presents an overview of recent trends of PV-powered vehicles in the world, and discussed expected benefits of PV-powered vehicles and measurements of solar irradiance on vehicles. Although more and more PV-powered vehicle projects are being started, further actions will be necessary to realise practical deployment of PV-powered vehicles. As next steps for realising PV-powered vehicles, potential benefits of PV-powered passenger vehicles, and issues for realising PV-powered vehicles, standardisation of solar irradiance and module design, and combination with PV-powered infrastructures have been explored.

Potential benefits of PV-powered vehicles in IEA PVPS Task 17 member countries

Based on the case studies on PV-powered passenger vehicles described in B, expected benefits of PV-powered passenger vehicles in IEA PVPS Task 17 member countries were estimated (see Fig. D-1).

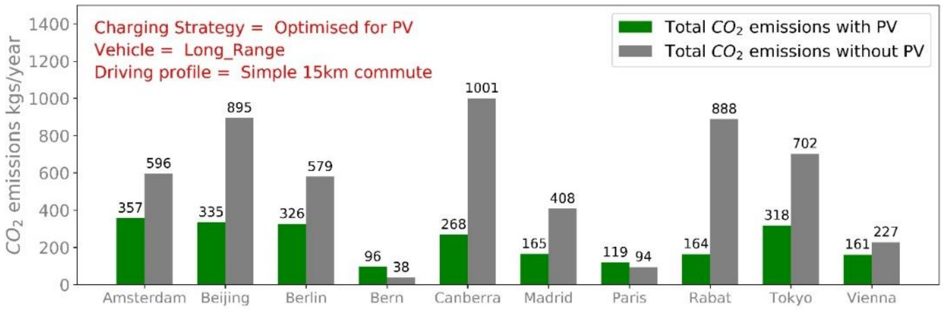


Fig. D-1 Comparison of CO_2 emissions for each location with and without PV
(The locations with the lowest local grid carbon intensity, Bern and Paris, both have no CO_2 benefit from the 800 Wp PV on the long-range vehicle for the simple 15 km commute driving profile.)

In most cases, CO_2 emissions are reduced during the operation of the vehicle by the on-board PV. However, in some cases, e.g. in countries with very clean grid energy, the embedded CO_2 based on the manufacturing of PV modules might lead to slightly higher lifetime emissions. In order to increase the CO_2 reduction achieved for all PV-powered vehicles, PV modules with lower embedded emissions are needed, in addition to higher efficiencies and/or longer PV component lifetimes. Well-integrated PV technologies such as curved, flexible and lightweight PV modules, in addition to higher efficiency PV technologies, will contribute to increased PV electricity generation.

These studies also find that maximizing PV utilisation is important in order to realise the maximum benefits of PV. The value of the PV utilisation ratio where the CO_2 emissions from PV electricity are equal to the CO_2 emissions from the grid corresponds to a crossover point where the PV powered vehicle goes from producing an increase in CO_2 emissions to providing a decrease or an environmental benefit. This point is equal to the ratio of 'CO_2 emission by PV electricity with 100% utilisation ratio' to 'CO_2 emission by grid' (see Fig. D-2).

This cross-over, or minimum PV utilisation ratio, has been calculated for each of the Task 17 countries' locations (see Fig. D-3). The minimum utilisation ratio required varies between locations. The higher the grid carbon intensity and PV generated electricity, the lower the required utilisation ratio. In most locations, the minimum PV utilisation ratio is less than 30%. When the grid carbon intensity is very low, as in Paris and Bern (not shown), the minimum utilisation ratio is above 100% indicative of the higher CO_2 emissions of the PV modules resulting in an increase in CO_2 emissions with PV on-board with current state-of-the-art technology. Research and development to lower embedded emissions of PV modules, as well as increasing efficiency and improved reliability of PV components is needed to increase the environmental impact on on-board PV, in terms of CO_2 emissions. These results do not currently consider the potential for trading battery capacity for on-board PV and the accompanying impact on lifetime CO_2 emissions.

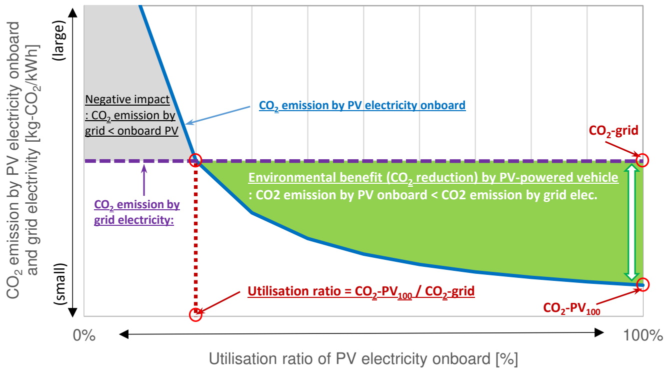


Fig. D-2 Image of relations between CO_2 emissions of PV/grid electricity, utilisation ratio of PV electricity, and CO_2 reduction by PV-powered vehicle

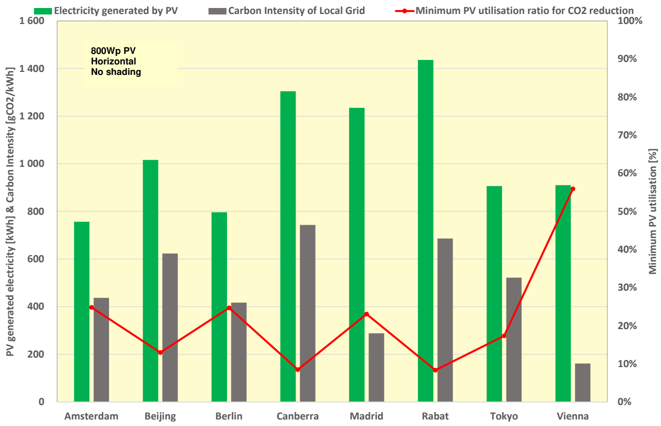


Fig. D-3 PV generated electricity and carbon intensity of the local grid (left axis) and the minimum utilisation ratio of PV electricity to begin achieving a CO_2 reduction (right axis)

(Bern, Switzerland and Paris, France have been omitted as they will not have a CO_2 reduction for the given example.)

Driving patterns and solar irradiance vary by region, country, and driver. In order to increase the level of utilised PV electricity, optimised design of PV-powered vehicles with respect to PV capacity considering effective solar irradiation and vehicle efficiency, battery capacity and efficiency and the operating condition is required. On the other hand, increasing the utilisation ratio of PV electricity also avoids surplus PV electricity. One of the most promising approaches will be to provide PV electricity to surroundings when the PV-powered vehicle is parked, i.e. V2X. Another approach to maximise PV utilisation is managing the battery's state-of-charge (SOC) to ensure that enough capacity is available for storing on-board PV electricity. When reserved capacity for PV electricity is well-managed, demand for grid electricity is reduced and less PV electricity generated on-board will go to waste.

Issues for realising PV-powered vehicles

PV modules integrated into vehicles are a part of a PV system, and as well, part of the components of vehicles. The product will be tested and rated by two standards. For example, the performance of the PV module will need to be verified as a PV system with necessary corrections by the different usage such as moving, frequent shading, etc. At the same time, it is to be tested as an exterior component of vehicles, such as different types of glass. And it is also to be tested as a vehicle's electrical component.

The standard PV modules are installed in such a way to avoid shades on the installation. However, PV modules on the vehicle's roof are not oriented to optimise for the utilization of solar energy. The driver's parking preferences may often lead to shade being cast on the PV. The relative orientation of the PV on the vehicle to the sun's position is not fixed but frequently changes by driving. The PV on the vehicle's body and the vehicle's roof is curved. It is often shaded by its own surfaces. Therefore, the methodology for performance analysis needs to be reconstructed.

For the moment, there is no published standard as well as no records of publications of official activities for the international standardisation. In order to establish standards for solar irradiation and module design for PV-powered vehicles, rating tests, design qualification, power modelling and energy prediction will need to be addressed. The following vehicle-specific issues will need to be considered: greater chance of shading by objects around the vehicle (trees and buildings), curved surface, varying orientation angles, and mismatching loss by partial shading. As discussions for standardisation will be done by another body like the IEC, technical requirements for PV installation into a vehicle's body will be discussed more in Task 17's next steps.

As another issue, in order to effectively use the PV electricity generated on-board, the potential of PV applications for electric systems and infrastructures will need to be addressed. The combination of PV-powered vehicles and charging infrastructures takes advantage of PV-powered vehicles: PV production impact in stationary mode, requirements regarding the charging infrastructures, and PV benefits when services such as vehicle-to-grid/home/vehicle are available at charging terminals.

Regarding the PV-powered charging infrastructure with a PV vehicle parking shade, the PV-powered vehicles may present maximum PV benefits while parked outside the shade of the station; therefore, an additional study related to the station design is required. Although it will not change the V2X design and technology, the PV electricity produced and stored by PV-powered vehicles can be used as an additional flow of electricity for all the V2X services. However, the real "additional value" earned from vehicles powered by PV is the PV electricity real-time production during the time the vehicle is parked, on public parking or at home. In addition, regarding V2H, if at home the vehicle owner does not have a PV installation, the PV benefits provided by the vehicle could be increased.

These issues will be analysed in Task 17's next steps, which includes the following objectives: requirements, barriers, and solutions for PV-powered infrastructure charging stations, feasibility conditions, and V2X services offered by the PV-powered charging stations.

The way forward

PV-powered vehicles may offer significant benefits to drivers and may offer an important contribution to the energy transition. Their market introduction will require technical optimisation of the PV but also of vehicles and vehicle use. Short driving range commuter vehicles, ultra-light weight vehicles, and high efficiency EVs are the most realistic concepts to apply PV power for smaller passenger vehicles. As a concept of bridge technology to PV-powered vehicles, it will be possible to consider PV-equipped vehicles for auxiliary components such as air conditioning systems, refrigerators and heating systems. This can already be seen in some passenger vehicles. For heavier commercial vehicles such as truck trailers, other goods delivery vehicles, and buses, on-board PV can make significant contributions to these auxiliary systems and the electric conversion of these systems. Taking into account the area available for PV and the possible use of PV electricity for auxiliary demand, PV-powered refrigerated truck trailers and buses are close to market introduction.

The questions of how to directly use and manage PV electricity for different types of vehicles, driving profiles, and locations with different solar irradiance, and how to integrate PV components on-board with keeping mechanical and physical reliability and safety including standardisation will be important for all kinds of PV-powered vehicles.

In order to effectively use the PV electricity generated on-board, an integral approach with PV applications for electric systems and infrastructures will be important. This may also contribute to reducing the impact of widespread PV generation and EV charging on the stability of the grid.

The PV market in the transport sector is still small. However, the potential impact is large and the electrified transport market will be a key driving force for the further development of PV in the coming years. PV-powered vehicles have the potential to further decrease the CO_2 emissions impact of electrified transport (particularly in the short term) and accelerate the adoption of electric vehicles overall due to decreased dependence on the grid. In order to utilise the potential and to realise PV-powered vehicles, expected benefits should be further validated and evaluated from viewpoints of not only energy, the environment, and from the perspective of users, but also the related industries, and shared with stakeholders such as automotive companies and relevant policy organisations.

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