Final report PV in Mobility (PViM)

Project information

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- Project title: Photovoltaics in Mobility (PViM)
- Project manager and participants: Nederlandse Organisatie voor Toefepast Natuurwetenschappelijk Onderzoek (TNO, penvoerder), Universiteit Twente (UT), Ildiz & Meijers Business Group B.V. (IM Efficiency), Atlas Technologies B.V. (Lightyear), Trens B.V. (Trens), DSM Adanced Solar (DSM)
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Copies of this report can be requested from TNO, free of charge.

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Summary

The goal of the PV in Mobility project was to further explore the possibilities for photovoltaics (PV) in the future electric transport industry. As transportation transistions from fossil fuel based to a largely electrified sector, it is expected that this will increase the electrical demand on the grid in the Netherlands by as much as 20%. Therefore, in order to realize climate goals, supply of this electricity should come from renewable and sustainable energy sources.

TNO and the University of Twente, together with representatives of the new Solar Mobility industry in the Netherlands, namely, Lightyear, IM Efficiency, Trens, and DSM, researched the technical challenges, barriers, and potential value propostions and business opportunities for products and services focused on powering electric mobility with PV systems. The PV in Mobility project was focused beyond the concept of PV installed in large utility plants and feeding electricity onto the grid. While this will play a major role, the PViM project found the potential for more than 50% of the energy needed to fuel transportation could be produced by distributed PV solutions. These solutions fall into two categories: distributed stationary PV, and PV integrated in vehicles (VIPV).

Distributed stationary PV systems are systems such as PV integrated into bus stops, train stops, car parks, and microgrid systems in neighborhoods and communities. We found that many commercial solutions exist or are being tested at the pilot level. Systems can be owned by individuals (at a home), neighborhoods or co-ops, large or small private companies with a carpark, public transport companies, or city or regional governments. The business models include directly selling the electricity or offsetting electricity costs, improving logistics, potential for carbon credits, and even strategic combinations of energy generation and storage in order to sell back to the grid at opportune times.

The PViM also looked into new concepts for stationary distributed PV charging of electric vehicles considering bus stops and train stops. The first is a PV charging station bus stop with exchangeable batteries for buses. The second is a beautifully integrated train or bus stop with PV panels as the shelter material. Both systems would offer urban zero- to very low-emission public transportation options with aesthetic packages and appearance. Similar concepts could also be used for charging of e-bikes or other vehicle on a specific delivery or passenger route. However, there were two key issues for these solutions identified. In both cases, in the Netherlands, the proposed area available for PV would likely supply only about 50% of the energy needed. Secondly, there would be a need for fast rates of charging either of the batteries or the vehicles, that may be difficult to achieve without additional storage buffering.

On-board PV or vehicle integrated PV (VIPV) was the second option that the PV in Mobility project consortium considered. The industrial partners, are all involved in developing these kinds of products. This technology is at a much lower overall stage and is only now becoming commercially available in the Netherlands. As such, the PV in Mobility project focused on better understanding of the potential benefits and challenges that will exist for this technology to reach the market in the Netherlands. This was a four step approach:

1. We conducted an evaluation and measurement of the amount of PV resource that could be generated on-board of a typical passenger car driven by a typical driver in the Netherlands.
2. Based on these measureents, we modelled the expected performance and annual yield of a VIPV system in the Netherlands and other EU countries to quantify the benefits. We found that VIPV on a typical EV in the Netherlands could produce about 25% of the necessary vehicle energy annually, save approximately €150/year and save about 300 kg of CO_2 emissions annually as compared to grid charging, in addition to providing EV users more convenience, autonomy and confidence in their vehicles.
3. We then evaluated the value propositions and business opportunities for VIPV systems on different types of vehicles and found that there is significant market for VIPV manufacturing on the global level.
4. Finally, we developed two initial design concept studies of new or other applications of this technology: a solar powered mobile charging unit with PV charged batteries; and a solar electric luggage carrier to improve sustainability of the airport environment.

Finally, the PViM project was further focused on ensuring that the result of this study were disseminated and shared with a larger audience. This work resulted in five publications, nine invited presentations, an international workshop event with more than 100 participants, and contribution to a International Energy Agency PV Power Systems Task 17 on PV & Transportation report, to be published in early 2021.

1. Introduction

1.1. Objectives

The PV in Mobility project was proposed and exectured in order to research the role that photovoltaics (PV) could play in electric vehicle (EV) charging in the Netherlands (PV2EV). In the Energy Transition, one key goal is the transformation of transportation for people and goods become electric. EVs have zero tail-pipe emissions, but depending on the electricity source, the usage emissions, while improved, can still be considerable. One solution is to simply ensure that the entire electrical grid is powered by sustainable sources like wind and solar. Thanks to recent cost reductions for PV technology, this is financially viable. However, due to limited land, particularly in the Netherlands, there is desire to find innovative applications of PV. For transportation, this means taking advantage of the distributed nature of PV and installing PV near, or even on, vehicles and charging points.

In this project, we have identified and anlysed a number of different PV2EV charging systems that could be possible in the Netherlands and other countries. This includes both stationary and mobile PV2EV charging solutions (Figure 1), namely:

- PV powered public charging stations;
- Battery exchange stations with PV charging;
- Residential PV to EV solutions; and
- Vehicle integrated PV (VIPV).

We have evaluated these options in terms of utility, technology, cost and potential benefits at all levels of the value chain and with a focus on the use cases in Holland. This results in three main objectives.

Stationary Distributed PV2EV Solutions. For the stationary charging solutions, we compared the different ideas and how they might best be deployed. The consortium then built upon that evaluation in order to suggest improved designs and concepts for stationary PV2EV solutsions.

VIPV. Due to the low developmental stage (not commercially available yet), in order to better quantify and understand the potential benefits and weaknesse of integrated PV, we performed mobile irradiance and driver use measurements. These were implemented in a modelling script which allowed us to evaluate the value proposition for solar electric vehicles in the Netherlands as well as identify areas in need of further development and research.

Community Building. The final objective was to create a better community for exchange of ideas and data to accelerate the use of PV2EV solutions. This was intiated in an internationally offered online workshop to share the disseminate results of the project with more than 100 registered participants. From these activities, a new international Alliance for Solar Mobility, ASOM, has been formed with the intention to form a community of industry, knowledge institutes and universities willing to cooperate in a pre-competitive environment to make sustainable transportation available to all.

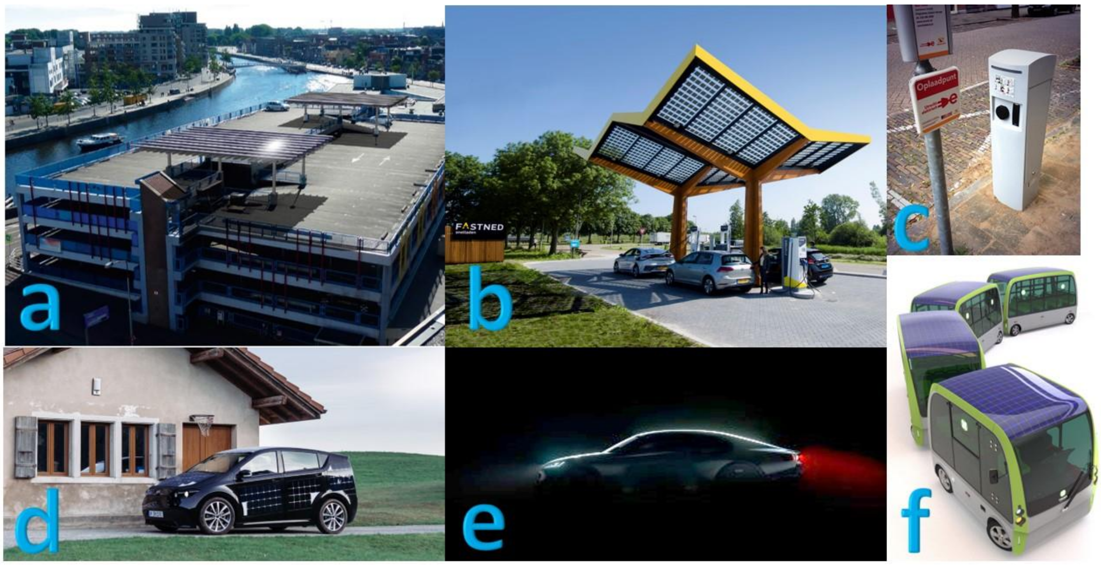

Figure 1. Examples of different PV2EV systems. a) Gemeente Alkmaar - small grid connected system for 6 charge points on local public car park,(Source: RVO link) b) Fastned - fast charging PV powered systems, (Source: Fastned link) c) LomboXnet - First solar-controlled V2G public AC charging station in the world - June 9th 2015. 44kW grid connection d) Sono motors Sion PV powered EV, (Source: Sono link), e) Lightyear one Dutch designed PV powered EV in development, (Source: Lightyear link), f) Trens Solar Trains, Dutch multifunctional solar-electric vehicles, (Source: Trens link).

1.2. Consortium

The consortium of PV in Mobility involved TNO and University of Twente as the core research team with input, data, and consultation provided by four companies from the solar mobility industry in the Netherlands. All three companies are currently working on VIPV solutions for PV2EV charging btu in different modalities. Atlas Technologies is developing a passenger car, the Lightyear One, with a highly efficiency design with an integrated PV system designed to significantly charge the traction battery of the car. IM Efficiency is offering the Solar on Top technology for auxiliary system power in truck trailers. TRENS is developing a wireless all electric ''train'' sutiable for refrigerated goods delivery or people moving in inner cities, parks, or other locations. DSM develops material solutions for PV modules which could potentially be applied in PV in Mobility applications .

2. Project results and follow up work

We first evaluated the new electrical demand that electrifying the transport sector will require. We find that no one solution is a perfect fit and that a mix of solutions and products will likely need to be innovated and offered to consumers and government in order to meet the needs. In the second part, we will address the potential options for both stationary and on-board (VIPV) systems to power various vehicles, and finally we will analyse a the business case of some potential products, what issues may remain, and who will realize benefits.

The results of WP3 on dissemination and outreach will be outlined in terms of the workshop impact, publications and contributions to the IEA PVPS Task 17, new intiatives, and further activites.

2.1. Infrastructure and PV Resource

There are four basic ways to use distributed (without the grid) PV for EV charging: stationary or mobile and integrated on the car as captured in the first two pathways of Figure 2. In this work package, we had three main activities. We first looked at how much energy is needed for the Dutch fleet of EVs now and in the future, as well as what this would mean for PV. Secondly, for understanding the value of VIPV, we developed a setup to measure actual PV resource available on a moving vehicle and use this as input to a model to quanify potential benefits, and third, we compared the value propositions of mobile VIPV to stationary PV.

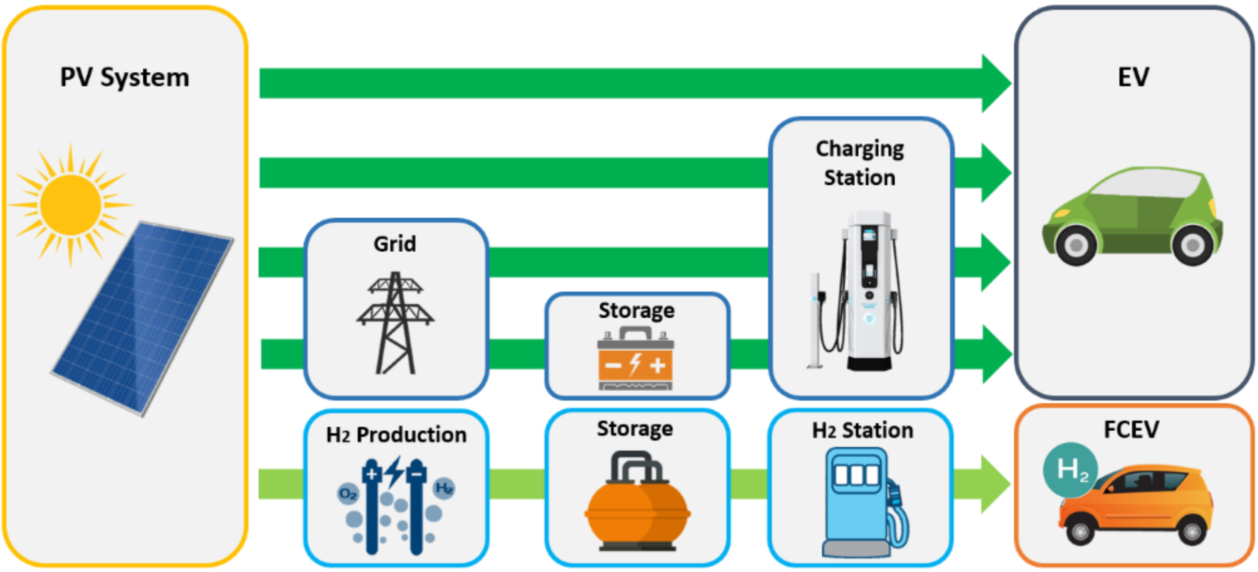

Figure 2. Schematic of options for PV to EV charging.

2.1.1. How much energy is needed for EVs?

Globally, there is a campaign to ensure that 30% of all vehicle sales in 2030 will be EVs. According to the IEA, for the EV30@30 outlook, the electrification of the transport sector will require and additional 1110 TWh of electricity per year. The Netherlands has been a world leader in adoption of EVs. In fact, during the running of this project, more than 140,000 additional EVs were registered[1]. The Netherlands has announced a goal that all new sales of passenger cars in 2030 should be zero-emission at the tailpipe. In addition to passenger cars, it is predicted that similar electricity demand in 2030 may also come from commercial vehicles like buses, delivery vans, and trucks. This will result in an additional 10-14 TWh of electricity demand each year by 2030, or about 20% of the 2020 electricity demand. This will also likely increase by approximately 1TWh – 1.4TWh per year as new EVs continue to replace existing cars.

It is imperative for the energy transistion, that this added electricity demand is supplied by sustainable and renewable energy sources like solar and wind.

2.1.2. Where can the PV be installed?

Supplying this with PV will ensure that the electric transportation system is not only zero-emission at the tailpipe but also zero-emissions for the full use cycle of the vehicle. If we look at the approximate requirements for both passenger cars and trucks, the Netherlands will require approximately 12 – 14 GWp of PV installation dedicated to powering vehicles by 2030. In turn, this equates to about 12,000 to 14,000 hectares or 6-7 million residential rooftops. This corresponds to roughly tripling the cumulative amount of PV installed in the Netherlands by the end of 2020. Of course, wind and other renewable resources will also supplement solar.

A major benefit of PV is the modular and distributed nature. In order to increase the overall efficiency, the PV resource should be located as close to the point of use as possible. Residential installations and local charging points with integrated PV can offer this as well as integrating PV on a vehicle. A Tesla Model 3, the most commonly registered new car in the Netherlands, has approximately 4 m^2 of sun facing area. If efficient PV integration can be achieved, we could expect to be able to install about 800 Wp of PV on a vehicle based on current commercially available efficiencies. On a truck trailer or a bus, as much as 6 kWp could be effectively integrated on each vehicle. Therefore a fleet of 2M passenger cars and 200k trucks and buses with integrated solar could annually contribute approximately 7 TWh of

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[1] https://www.rvo.nl/sites/default/files/2020/11/Statistics%20Electric%20Vehicles%20and%20Charging%20in%20The%20Netherlands%20up%20to%20and%20including%20October%202020%20-%202.pdf

electricity per year, approximately half of the overall demand. Of course, it is unlikely in the near future that on-board PV will be able to generate all or most of the energy demand of the transportation fleet, so grid solutions are also important. These include solutions such as PV covered parking lots, PV integrated in parking structures, and community PV powering specific charge stations in fully-isolated or semi-isolated grid systems.

2.1.3. Implications for smart cities and smart grids

There are already a number of intiatives looking at the potential of using EV batteries as mobile power storage in the smart cities of the future. A vehicle with batteries on it could charge in one location at a specific time and discharge in another location and time improving grid stability and variability issues. With onboard PV, the business opportunities in this area could greatly expand. At this moment, no solutions or commercial schemes exist, but in WP2 we looked at some of the potential opportunities.

2.2. On-board PV solutions

On-board PV is identified as a promising solution potentially able to provide as much as 50% of the new energy demand from electric vehicles. It is a new application for PV and will require further research, innovation, and invention. The PViM project focused on doing measurements and modelling of the potential impact and translating that to value propositions and business cases.

2.2.1. PV Irradiance Measurements – Available PV Resource for on-board PV

One of the key issues addressed in WP1 is measurement of available irradiance for moving PV. Unlike conventional stationary PV, on-board PV will see a very dynamic and always changing irradiance and ambient environment including reduced irradiance, partial shading, moving shade, and highly variable temperatures. TNO built a vehicle irradiance test setup (VITS) pictured in Figure 3. This setup used 4 irradiance sensors, one in each corner of the roof. The solar panel in the middle is to used to power the system but not for measurement. As seen in the right side of Figure 3, the four sensors are used in order to better approximate the solar irradiance that is available on the vehicle at any time as the car roof is not always in full sunlight.

The system also measures ambient temperature and records the GPS location of the vehicle, Figure 4. This gives added information in order to better approximate annual yield of a solar system. The GPS information was used to locate the vehicle and to compare the local stationary irradiance measurements provided by KNMI. As seen in Figure 5, the average irradiance, can be approximated by the local KNMI data to first order as long as the car is not shaded by a building or other object.

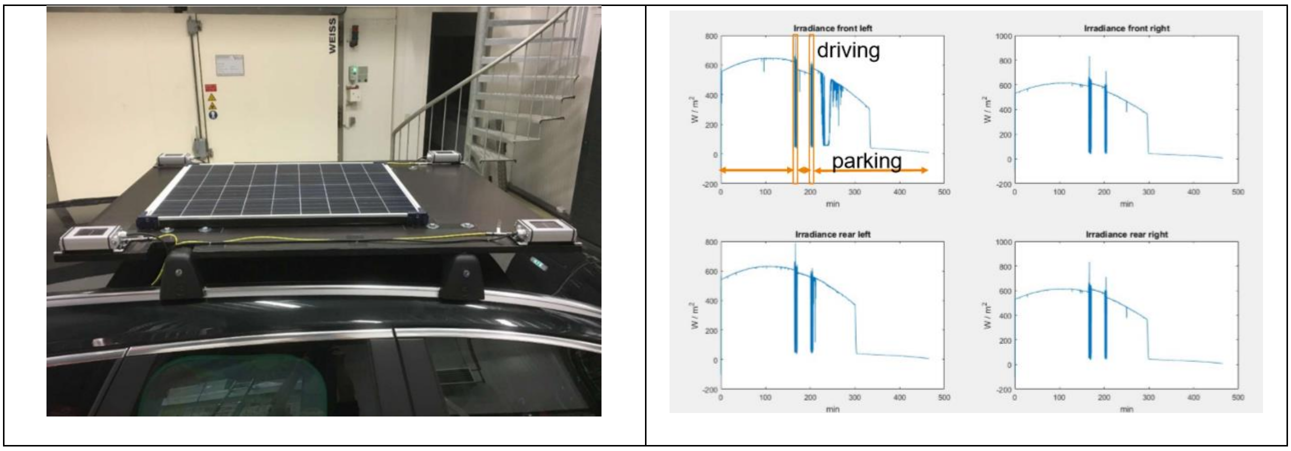

Figure 3. Vehicle Irradiance test setup (VITS) (left) Photo of the system as installed on a car for measuring realistic driving profiles and available mobile irradiance and (right) an example of a results from the four sensors on the four corners of the car.

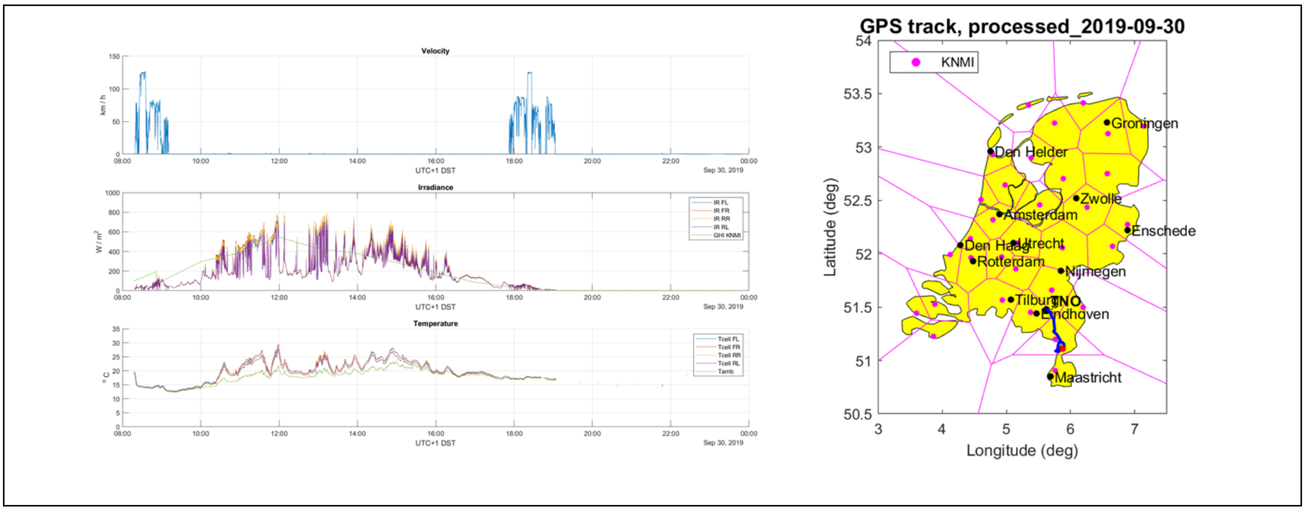

Figure 4. Example of VITS data collected including velocity, irradiance and ambient temperature. For first modelling purposes, it was verified that on average the irradiance measured at a nearby meteo station approximated the measurement on the vehicle.

Further work on the impact of shading, and partial shading will be needed to further account for these differences. This is beyond the scope of the PViM project but more work and more vehicles are needed to create a large enough data set in order to better understand and model the situational partial shading environments and the impact that shade will have on the potential energy yield.

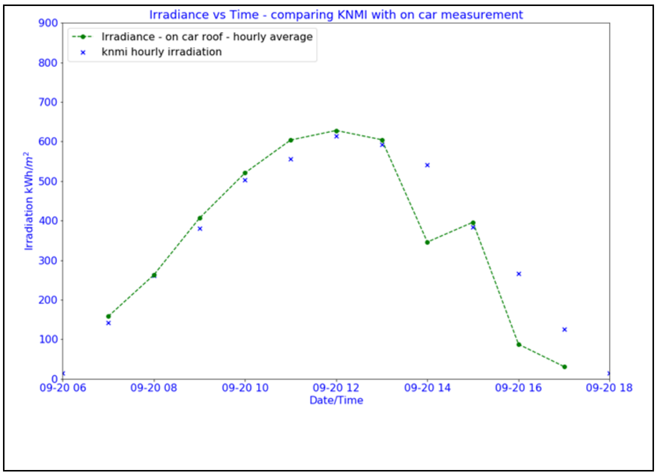

Figure 5. VITS average measured irradiance vs. local KNMI station data.

The VITS system also gathered data on real driver use profiles. This is important information in order to better understand how vehicles are used by drivers as this will directly impact the consumption energy of the vehicle as well as the location, parking behaviour, etc. In Figure 6, we show two types of driving profiles. On the left is a simple synthetic profile assuming a 20km commute each way, five days a week. On the right, is the measuered driver profile. It is much more detailed and reveals a better approximation of the overall impact that on-board PV could have for a real driver.

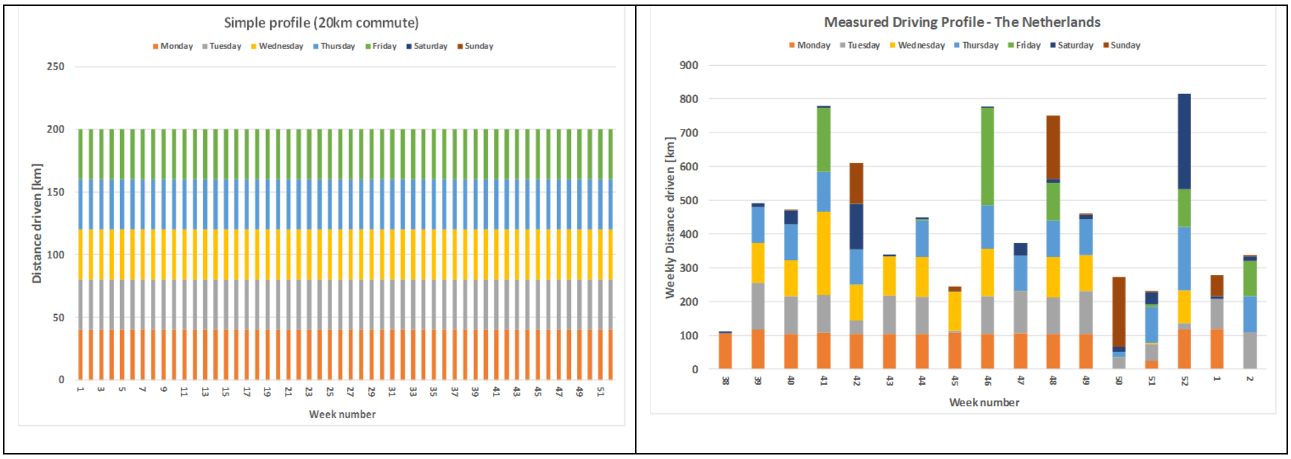

Figure 6. Driving profiles used in modelling. Left is a simple synthetic profile and the right is the measured profile collected from the VITS system.

2.2.2. Modelling of Energy Flow and Yield

In order to evaluate the impact, the PViM consortium developed an energy flow model. A schematic of the model can be seen in

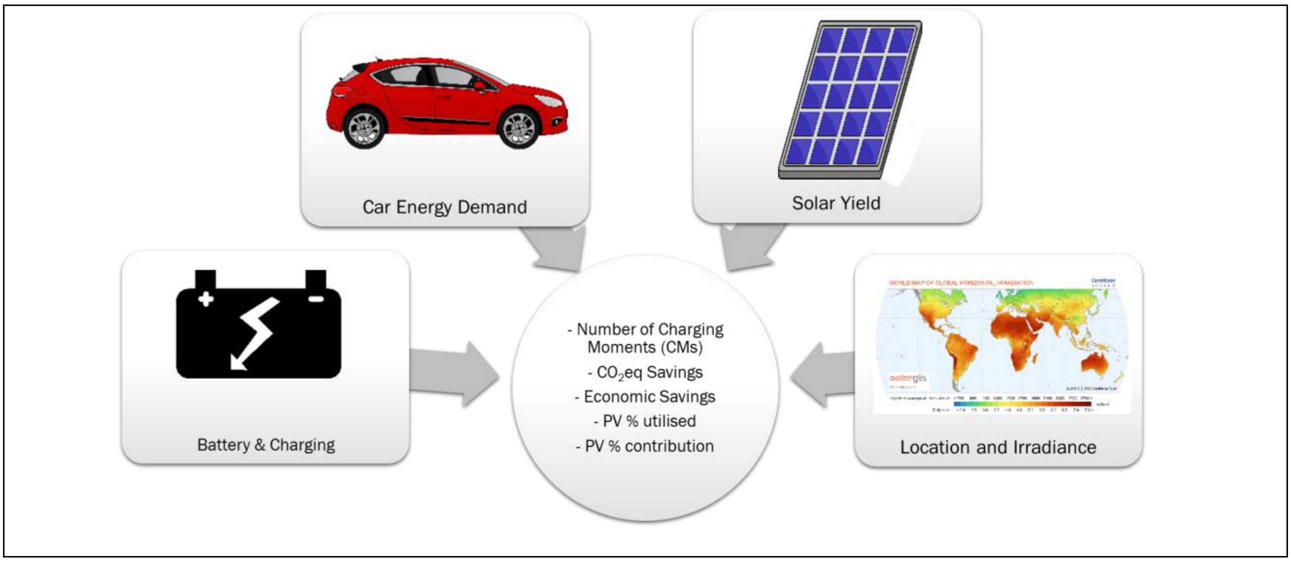

Figure 7. Schematic of the energy flow model used to quantify the impact of on-board PV on a passenger vehicle.

Essentially, this is a model that performs and energy balance for the vehilcle on 10 minute time-steps through out the year according to the equation:

$$E_{PV} + E_{grid} = E_{EV} + E_{bat} + E_{unused}.$$

Here, E_{PV} is the energy generated by the PV system, E_{grid} is any energy collected from the grid (if parked), E_{EV} is the energy used by the vehicle for both traction and accessories and also includes charging losses, E_{bat} is energy used to charge the battery, and E_{unused} is any energy that can not be used immediately. Based on this model, we can perform a detailed modelling that helps us to understand the real impact of on-board PV.

The model results in specific benefits of the PV in terms of

- Convenience, or the number of avoided plug-in grid charging moments

- Range extension in terms of the number of annual km that can be driven on solar power alone (percentage of PV contribution)
- Annual CO2 savings and offsets as compared to always charging an EV from the grid
- Annual Cost savings as compared to charging a vehicle at home
- Efficiency of the system and charging strategy in terms of the percent of PV utilized

The result of this modelling is highly dependent on the location, vehicle efficiency, charging strategy, battery capacity, driving profile and of course the actual irradiance that year. That is the strength of this method is that we can easily modify those. More details and more simulations can be found in the reports and presentations listed below. In this summary, we will focus on the results for a long-range EV like a Tesla Model 3 and a mid-range EV like a Nissan Leaf driven in and around Amsterdam.

Table 1. Summary of energy flow model outcomes for a 13,000 km per year driving profile similar to the Dutch average based in Amsterdam. The VIPV system is rated at 800 Wp under STC conditions. Cost and CO_2 savings are based on €0.217/kWh for home based charging, and a grid cabon intensity of 437 gCO_2/kWh. All numbers are reported on an annual basis.

	Solar kms per year	**Potential PV Generation (% of total energy dem.)**	**Reduced Grid Dependence (reduction of grid chargin moments)**	**Savings (€/year)**	**Avoided CO_2 – emissions (as compared to grid) (kg/year)**
Long-range	3473	26.7%	21%	€161	308
Mid-range	3044	23.4%	19%	€153	301

Here we see that mor than 25% of the annual energy demand can be met with the on-board PV resource and one out of every five plug-in charges can be avoided. Over the lifetime of the vehicle (assumed to be 12 years) the PV should save approximately €2000 and avoid almost 3700 kg CO_2 emissions as compared to the grid. In sunny countries, such as Spain, the benefit could be much greater while in other countries like Sweden the benefit is greatly reduced due to lower irradiance and a cleaner grid system.

2.2.3. Life cycle analysis of on-board PV

In order to better understand the potential environmental impact of VIPV the PViM consortium also performed a more complete life cycle analysis (LCA) for cradle to grave emissions. This will take into account the embedded CO_2 in the vehicle, battery, and PV system from manufacture and raw materials as well as in the use phase. In this case, the analysis was based on a Nissan Leaf with and without on-board PV. Both vehicles are driven (and charged) in Amsterdam for 12 years with a total of 180,000 km over the total lifetime. For the VIPV Nissan, the battery capacity is slightly reduced and 40% of the energy is assumed to come from the solar system.

The results are seen in Figure 8 and shown in comparison to a typical EV (less efficient) from literature, a typical internal combustion gasoline engine vehicle, and an in internal combustion diesel engine vehicle. The results are in g of CO_2 per driven km. As can be seen, the standard EVs offer only moderate savings as compared to a gasoline ICE and are in line with the diesel ICE. This is mostly due to the 2017 mix of the Netherlands grid, 541 g CO_2 eq. green house gas (GHG) emissions and the embedded CO_2 of batteries. By avoiding the grid, the VIPV equipped Nissan Leaf (with a slightly smaller battery), emits 110 gCO_2 /km as compared to the normal Nissan at 152 g CO_2/km. This corresponds to a 27.6% decrease in CO2 emissions.

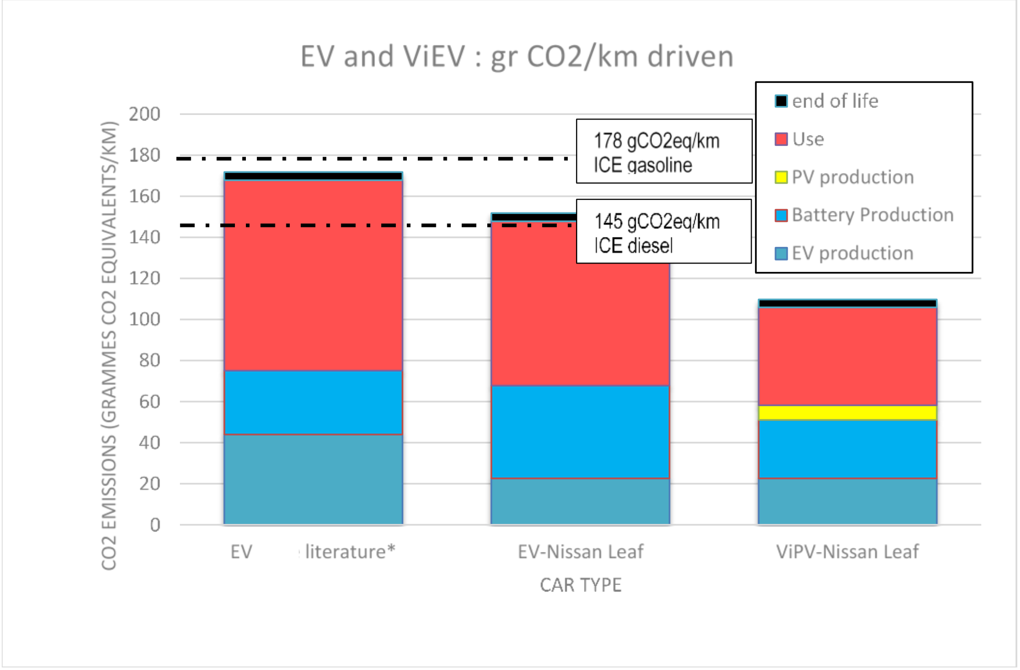

Figure 8. Summary of results of LCA for VIPV Nissan Leaf as compared to a normal Nissan Leaf, a typical EV, and internal combustion engines.

This comparison is heavily dependent on the CO2 content of the grid electricity and the vehicle efficiency. It should be noted that by 2030, the aim is to have a higher share of renewables on the grid in the Netherlands overall improving the grid footprint which would reduce the LCA of all three EVs as compared to the ICEs, and also thereby reducing the impact of the VIPV equipped Nissan Leaf. Additionally, it is also expected and imperative that the EVs become more efficient.

Based on the LCA, measurements, and modelling the PViM consortium finds that VIPV, even in the Netherlands, can offer both convenience, cost savings and contribute significantly to the energy transition goals. These benefits can also be realized in most other places in the world.

2.3. Other PV2EV Solutions for Netherlands Market

As seen above, VIPV can only account for, at most, approximately 50% of the energy demand from electrifying the transportation network in the Netherlands. Therefore, stationary charging stations will be necessary to supply the remainder of this energy.

2.3.1. Conceptual designs for PV2EV solutions

Here we outline four case studies for stationary PV2EV solutions for different transportation modalities. These designs were initially developed by students in a the ‘Sources of Innovation’ course offered by PViM participant, Prof. Angèle Reinders, from University of Twente, with potential design improvements and alternative applications added by the PViM consortium.

Case study 1. Solar bus terminal with rechargeable batteries

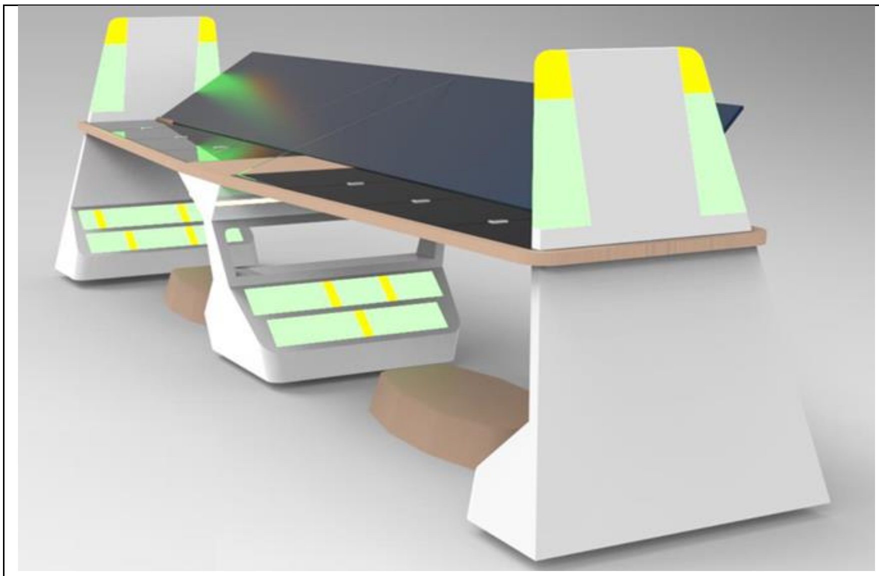

Figure 9. Solar bus terminal concept by M. Dijkstra, A. Suresh, adn S.V. Romana

This concept involved creating a platform with swappable and rechargeable batteries hat incorporates the function of a bus stop. Approximately 20kWp of conventional PV panels are placed on the roof of the bustop. Lights indicate charging status. Each swappable battery is about 25 kWh and easily carried by the driver. Since busses have limited time at stops, but have frequent stops, batteries could be swapped on a regular basis without disrupting scheduling. Battery swapping could also be replaced with the PV feeding a high capacitance central battery pack that would allow for rapid and high speed charging. This concept could also be used in other applications for passenger EV or e-bike charging.

Case study 2. Solar train stop

Figure 10. Solar train stop concept by S. Elango, U. Parvangada and G. Ribeiro.

The solar train stop concept illustrated in Figure 10 entails a making an aesthetic tree looking shelter with an integrated bench. The concept is scalable. The shade and rain protection would be provided by a ‘solar tree’ with approximately 1 kWp per bench. A 10 kWh battery would be integrated per bench in order to power an inductive charging point in the train line. A high charging speed would be required but this could be augmented by smaller on-board batteries to reduce the train's weight in increase the efficiency. This system could be coupled with PV on surrounding buildings to create a microgrid. Similar to the solar bus terminal a similar idea could be adapted for buses, e-bikes or other vehicles.

Case study 3. Lightyear Bus

Figure 11. Mobile charging unit concept by R. den Hertog, S. de Jonge and T. Willems.

The Lightyear bus, shown in Figure 11, is developed to further reduce range anxiety and fear of being stranded without charge for EV users, with or without their own VIPV. The bus is an effective mobile charging unit (MCU) with integrate PV panels that fold out to increase solar energy production. Generated power is stored in a battery bank that can be used to charge up to four EVs at the same time. As a sustainable MCU would offer drivers, particularly in areas with little infrastructure, more confidence in their EV use. Some further development is necessary with respect to weight, efficiency of the bus and the overall energy capacity. This concept could also be used in emergency or military situations to replace a diesel generator.

Case study 4. Solar-powered luggage vehicle

Figure 12. Solar-powered luggage vehicle concept by J. Liao, N. Pizzigoni and V. Rachmanda.

The solar powered luggage vehicle is a solution for more efficient airport environments and a way to decrease the overall carbon footprint of air travel. It is a fully autonomous electric vehicle to move luggage around the airport with integrated solar panels to power four in-wheel motors. Luggage loading and unloading is fully automated as well with a system of conveyer belts. Additional stationary PV may also be needed nearby in order to supplement the power on less sunny days.

2.3.2. Remarks of PV2EV solutions

For most of the PV2EV solutions, there is the same concern that the PV that can be installed on the vehicle or on the bus or train stand is likely not enough to fully power the vehicle in operation. This is a clear issue for all PV2EV solutions without the grid as part of the energy chain. This will be the case unless vehicles, of all kinds, can be made at least twice as efficient. Unfortunately, this is outside the scope of the PViM project.

2.4. Value Propositions for Various Transport Modalities

In this section we will discuss the benefits, market potential and technical challenges for three different market sectors. However first a short discussion on cost-price target for VIPV.

2.5. Cost-Price of VIPV

Based on the measurements and modelling in WP1 for passenger cars, we see that a VIPV system should save the user €150/year with an 800Wp system purely in terms of electricity savings. If we assume a payback time of about 5-10 years, this would be mean that the system cost-price should be between €0.94/Wp - €1.88/Wp. The current technology that is now being adapted for VIPV systems is built on the well established and low-cost supply chain of conventional PV. At the end of 2019, the average sales price of conventional solar modules was approximately €0.35/Wp. By 2025 it is expected to be about €0.12/Wp. Typically, hardware costs, including electrical balance of systems and inverter costs make up about 1/3 of the total cost of an installation, including profits. Assuming that VIPV can continue to take advantage of the low-cost existing supply chain, and installation will take place in the factory, then it could be reasonable expected that VIPV systems could be manufactured and installed on the car for approximately €1 - €2/Wp by 2025.

As noted before, this does not account for the value or benefit that could realized for on redueced carbon, carbon credits, road tax benefits, or convenience.

Case 1. VIPV on Passenger Cars

The project has resulted in the most detailed understanding of the business model VIPV on passenger cars due to the measurements and modelling in WP1. For this case, we are able to directly quantify some of the benefits.

ROI Target for Consumer: 5-10 years

Table 2. Potential benefits and value propositions for VIPV Passenger Cars

Benefit	Quantity	Who benefits
Reduced Charging Frequency	Reduction by about 20% compared to standard EV	Driver for added convenience and reduces ''range anxiety''
Reduced CO_2 emissions	Approximately 33% as compared to gas ICE; 20% as compared to standard EV;	Drivers concerned with fossil fuel savings and climate issues
Cost Savings	Payback time on the order of 5-10 years depending on tax credits and road use taxes	Driver/car owner
Carbon Credits	TBD	OEM for fleet emissions
Smaller batteries	TBD	OEMs,
Improved battery lifetime/reliability	TBD	Tier 1 suppliers of batteries, OEMs
Reduced load on grid	Potential of approximately 50%	Local, state, and national government

Market Potential: There are two basic market channels to introduce this technology, installation on current EVs either in production or after market, so-called solar assisted EVs or new solar EVs with better efficiency and designed around the VIPV concept. Global market opportunities are estimated in the table below according to IEA Global PV Outlook and assumed

Table 3. Global market estimations for PV on passenger vehicles

Solar Assisted EVs	**2020**	**2025**	**2030**
Available (millions of vehicles)	10	52	145
Addressable	0	0.5	1.5
MWp PV	0	250	750
Solar EVs			
Total (thousands of vehicles)	0.500	70	500
MWp PV	0.55	77	550

Technical Challenges: There are a number of technical barriers that need to be addressed and currently identified for successful market introduction.

- Reliability and design for manufacturing for fully integrated concepts
- Lightweight materials

- Methods to generalize design to multiple vehicles
- Electronics for 12V and 48V systems
- Backend / telematics systems
- Validated energy yield modelling and forecasting
- Improved performance under dynamic conditions
- Aesthetic integration.

Case 2: VIPV for e-Busses

Buses offer an enourmous area for VIPV systems. Due to the known route in an urban setting, electric buses are gaining in use and there are a number of commercially available options. Additonally, e-busses also have longer lifetime due to less vibrations and are quieter for use around the city. Typically these busses will charge either at the depot (often on with PV systems) or at strategically located charging points around the city. There is also great potential for on-board PV as there is approximately 13 m^2 sun-facing area. As the modelling was not extended to this application, we will only discuss what potential benefits are and who might enjoy them.

ROI Target for Bus Operator: 4-8 years

Table 4. Potential benefits and value propositions for VIPV e-Busses

Benefit	**Who benefits**
Reduced Grid Charging Frequency	Bus operator in terms of logistics or number of needed en-route charging stations or time at the depot
Reduced CO$_2$ emissions	Bus operators – clean image, potential for winning tenders, possible tax credits Bus manufacturers – increased sales due to overall fleet emissions
Cost Savings	Bus operators, bus users
Carbon Credits	Bus operators and bus manufacturers
Smaller batteries	Bus operators, reduced cost of battery replacement
Improved battery lifetime/reliability	Bus operators, battery lifetime may better match the vehicle lifetime
Reduced load on grid	Local governments and grid managers
Mobile battery packs	Bus operators may be able to create new business opportuntites as power providers

Market Potential: By 2030 it is expected that there will be about 7M e-busses globally. With the assumption that VIPV can be applied to 1% of these vehicles this would be an addressable market of approximately 700k, or in terms of PV, approximately 2 GWp.

Technical Challenges: The technical challenges are similar to those for passenger cars but the PV element probably does not need to curved and the aesthetics are less important.

- Reliability and design for manufacturing for fully integrated concepts
- Lightweight designs based on polymers
- Methods to generalize design to multiple vehicle manufacturers

- Electronics for 12V and 48V systems
- Backend / telematics systems
- Validated energy yield modelling and forecasting
- Improved performance under dynamic conditions.

Case 3. VIPV for Electric Light Commercial Vehicles

A third opportunity for VIPV are electric light commercial vehicles. Due to the COVID-19 pandemic, there is an increase of delivery by LCVs for groceries, packages, etc. Many experts think that the demand for such delivery services will likely continue and will help to drive the need for e-LCVs as cities require low emission transportation in urban and residential areas.

ROI Target for Delivery Company: 4-8 years

Table 5. Potential benefits and value propositions for VIPV of electric Light Commercial Vehicles

Benefit	**Who benefits**
Reduced Charging Frequency	Delivery company, logistics and drivers. Improves effective range and facilitates easier routing logistics for deliveries.
Reduced CO_2 emissions	Greener image for goods and delivery company. Possible tax credits.
Cost Savings	Fleet operator with 4-8 year payback time
Carbon Credits	OEMs or Fleet operator
Smaller batteries	Fleet operators
Improved battery lifetime/reliability	Tier 1 suppliers of batteries, OEMs
Reduced load on grid	Local, state, and national government

Market Potential: Prepandemic it was expected that there will be about 27M electric LUVs by 2030. Assuming that PV could be installed on 1% of these vehicles, there will be approximately a market of 300k vehicles or about 400 kWp of PV installation.

Technical Challenges: The technical challenges are similar to those for passenger cars but the PV element probably does not need to curved and the aesthetics are less important.

- Reliability and design for manufacturing for fully integrated concepts
- Lightweight designs based on polymers
- Methods to generalize design to multiple vehicles
- Electronics for 12V and 48V systems
- Backend / telematics systems
- Validated energy yield modelling and forecasting
- Improved performance under dynamic conditions

2.6. International VIPV Workshop

On 15 October, the PViM consortium held an online workshop. Approximately 100 people registered from both the PV and Mobility community in the Netherlands, surrounding coutries like France, Germany, and Belgium, as well as a small global audience. There were four speakers:

Prof. Kenji Araki – Univ. of Miyazaki, Japan – Solar Resource for VIPV is not as simple as you may imagine – 3D irradiance and 3D curved surfaces

Prof. Manuela Sechilariu – Alliance Sorbonne University, France – PV-powered EV charging stations: requirements dan feasibility conditions considering grid interactions

Dr. Alonzo Sierra and Dr. Cihan Gercek – University of Twente – Design driven research on photovoltaic mobility

Dr. Anna Carr – TNO Energy Transition – Quantifiying the benefits of On-board PV for Passenger Cars

The first two presentations were from the international community and the second two were based on the research from the PV in Mobility project. Additionally, there were presentations from all of the industrial partners.

The workshop also served as an announcement for the formation of the Alliance for Solar Mobility, ASOM. This initiative has been a direct outcome of the PV in Mobility project as the industrial advisory board members found that increased and shared communications, modelling, measurements, data sharing would be advantageous to realizing PV mobility projects on the market. More information can be found at http://ASOM.solar.

2.7. Conclusion and recommendations

The PViM project has resulted in four main outcomes, namely:

- Energy flow modelling of the potential for on-board PV for various vehicles and types and for various locations.
- Measurements of irradiance available on vehicles driving in the Netherlands.
- Novel conceptual design of four new PV2EV solutions
- Intial evaluation of the business potential for mulptiple market sectors for VIPV
- Excellent dissemination to a Dutch audience both industrial and general public, growing interest internationally.

We have found that on-board VIPV systems are likely a good opportunity, now and in the future in order to realize ensure that the future electric transportation sector does not detrimentally increase the load on the energy grid. It addition, it offers cost savings, convenience, flexibility and potentially other benefits for the prosumers of this technology. However, it will not be able to provide all of the necessary electricity and it is still important to install sustainable energy systems on the grid to meet this increased demand and maintain truly low or zero-emission transporatation.

2.7.1. Policy Recommendations

There are three key policy issues identified in this report that should also be considered in order to encourage the uptake of VIPV on passenger cars.

1. Updated emission standards that take into account full LCA of vehicles.
2. Tax or financial incentives to for lower carbon emissions and reduced load on grid.
3. Standards for safety and performance of VIPV systems.

2.7.2. Future Research

Similarly, the PV in Mobility project has identified a few areas that would benefit from further research.

Mobile irradiance measurements and sharing of data in order to better estimate the impact of shading from buildings, infrastructure, trees, or other as a function of road and trip type. It would be ideal for this data to be in the public domain and accessible for bothc companies and research institutions as well as consumers in order to better understand the market potential and design better products.

Improved understanding of the impact that mobile battery packs on buses, truck trailers and even passenger cars can have on the grid. This includes the potential to use this storage in order to smooth variability and increase the overall renewable energy resource.

3. Dissemination of results

3.1. Publications

Sierra, A., de Santana, T., MacGill, I., Ekins-Daukes, N. J. and Reinders, A.H.M.E., A feasibility study of solar PV-powered electric cars using an interdisciplinary modeling approach for the electricity balance, CO_2 emissions, and economic aspects: the cases of The Netherlands, Norway, Brazil, and Australia, Progress in Photovoltaics: Research and Applications, 28, 517–532, 2020.
Download link: https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3202

Sierra, A., Gercek, C., Geurs, K. and Reinders, A.H.M.E., Technical, financial and environmental feasibility analysis of photovoltaic EV charging stations with energy storage in China and the United States, Journal of Photovoltaics, 10.1109/JPHOTOV.2020.3019955, 2020.
Download link: https://ieeexplore.ieee.org/document/9189831

Kanz, O., Reinders, A., May, J. and Ding, K., Environmental impacts of integrated photovoltaic modules in light utility electric vehicles, Energies, 2020,13, 5120, 2020.
Download link: https://www.mdpi.com/1996-1073/13/19/5120

Sierra, A. and Reinders, A.H.M.E., Designing innovative solutions for solar-powered electric mobility applications, Progress in Photovoltaics: Research and Applications, 1-17, 2020.
Download link: https://onlinelibrary.wiley.com/doi/10.1002/pip.3385

Carr, A.J., van der Tillart, E., Burgers, A.R., Köhler, T., Newman, B.K., Vehicle integrated photovoltaics – Evaluation of the Energy Yield Potential through Monitoring and Modelling, EU PVSEC 2020, online.

Invited Presentations

Dr. Bonna Newman: Opportunities and challenges for vehicle intergrated PV, University of New South Wales, School of Photovoltaic and Renewable Energy Engineering Seminar, Sydney, Australia, February 2020.

Dr. Bonna Newman: How the Netherlands is making solar powered cars a reality, University of New South Wales, Digital Grid Futures Institute, Sydney, Australia, February 2020.

Dr. Bonna Newman: Solar Cars: Challenges and Opportunities, TÜV Module Forum, Köln, Germany, February 2020.

Dr. Anna Carr: VIPV – Examining Use Cases with the TNO Energy Flow Model, ETIP I3PV Virtual Conference, online, November 2020.

Dr. Anna Carr: Quantifying the benefit of VIPV, Solar Mobility Forum, online, September, 2020.

Prof. Angèle Reinders: Design-driven research on solar PV-powered mobility, Invited presentation, PVSEC-30, Jeju, Korea, online, 2020.

Prof. Angèle Reinders: Design-driven research on solar PV-powered mobility, Distinguished Lecturer presentation, IEEE EDS Mini Colloquium, Taragona, Spain, online, 2020.

Prof. Angèle Reinders, Univ. of Twente: Design-driven research on photovoltaic technologies – System performance and solar integration in buildings, mobility and our environment, Keynote presentation, 7th International Academic Conference on Places and Technologies, Belgrade, Serbia, online, 2020.

Prof. Angèle Reinders, Univ. of Twente, Design-driven research on photovoltaic technologies – System performance and solar integration in buildings, mobility and our environment, Keynote presentation, IEEE Photonics North Conference, Niagara Falls, Canada, online, 2020.

3.2. PR activities of the project and future PR opportunities

VIPV is a topic that has recently captured the attention of the press. As such there have been a number of public relations events that have stemmed from the project.

Podcast. The Driven. How Close are we to Solar Cars? https://thedriven.io/2020/02/24/the-driven-podcast-how-close-are-we-to-solar-cars/. February 2020.

TV. NOS Journaal. Solar on truck trailers. https://www.npostart.nl/nos-journaal/09-09-2020/POW_04508411 Starting 18:30, 9 September, 2020

TV. NOS Nieuwsuur. Solar on passenger cars. https://www.npostart.nl/nieuwsuur/24-01-2021/VPWON_1324107 Starting 23:20, 1 January, 2021

PV Magazine Interview. https://www.pv-magazine.com/2021/02/24/vehicle-integrated-pv-reduces-ev-charging-time-in-sunny-regions-by-40/ 24 February 2021.

ASOM has a working group focused on PR activities. Outcomes from this project will be further disseminated through this alliance.

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 m^2 and 215 Wp/m^2 may provide up to 70 km/day. Additionally, CEA-INES developed a prototype vehicle equipped with 1,3 m^2 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,

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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/)

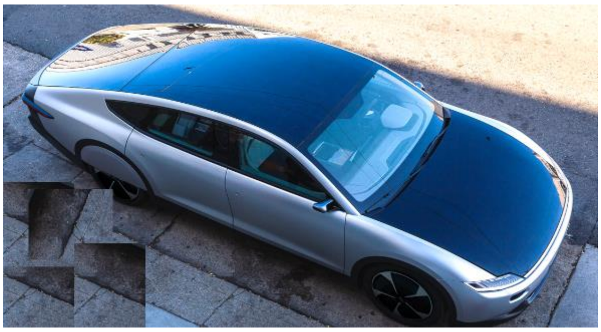


Fig. A-2 Lightyear One
(https://lightyear.one/lightyear-one)

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)

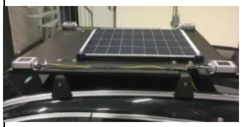
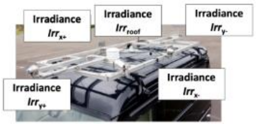
C. Solar irradiance for PV-powered vehicles

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).

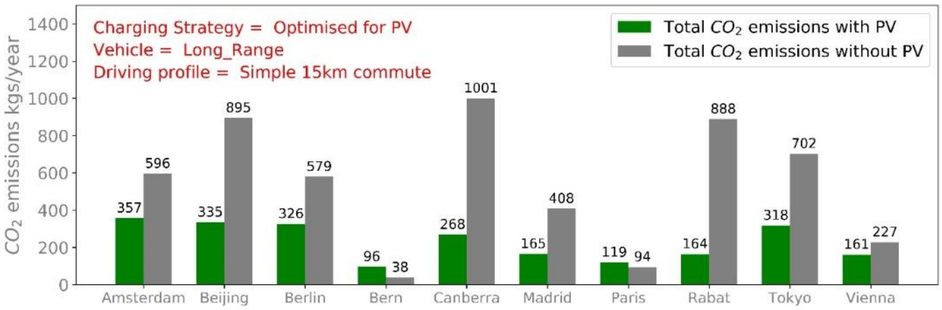


Fig. D-1 Comparison of CO_2 emissions for each location with and without PV

(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.

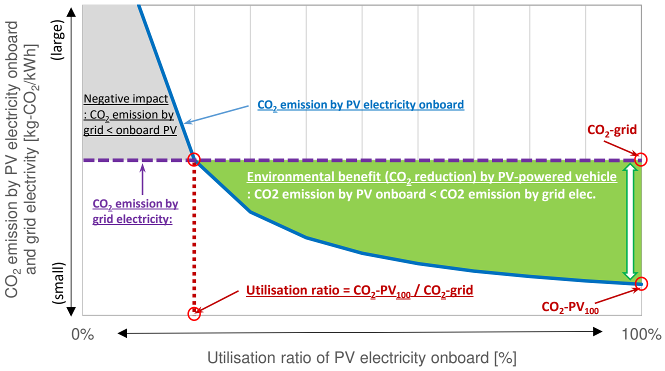


Fig. D-2 Image of relations between CO_2 emissions of PV/grid electricity, utilisation ratio of PV electricity, and CO_2 reduction by PV-powered vehicle

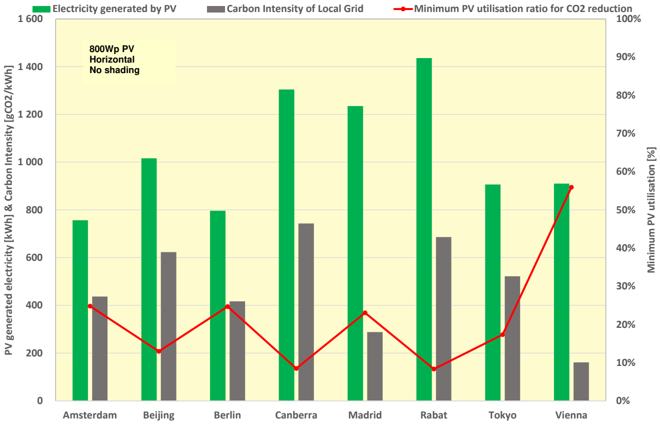


Fig. D-3 PV generated electricity and carbon intensity of the local grid (left axis) and the minimum utilisation ratio of PV electricity to begin achieving a CO_2 reduction (right axis)
(Bern, Switzerland and Paris, France have been omitted as they will not have a CO_2 reduction for the given example.)

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.