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

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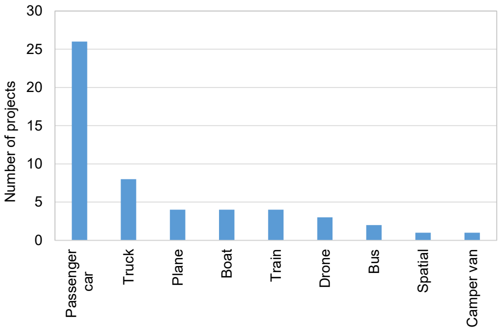
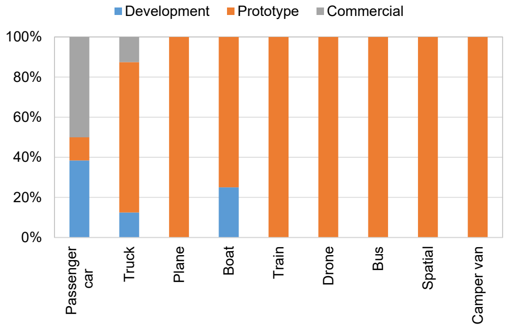
Table of contents

Trends in PV-powered vehicles development

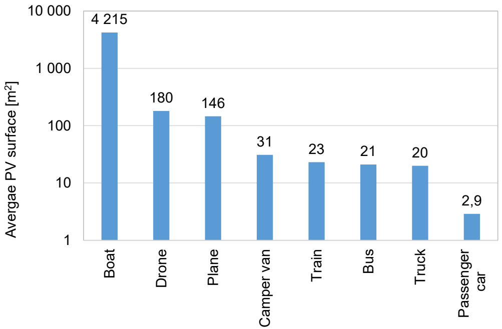
The majority of PV-powered vehicles development is passenger car-based projects.
Although expected available area for PV is small, the number of projects are rapidly increasing.

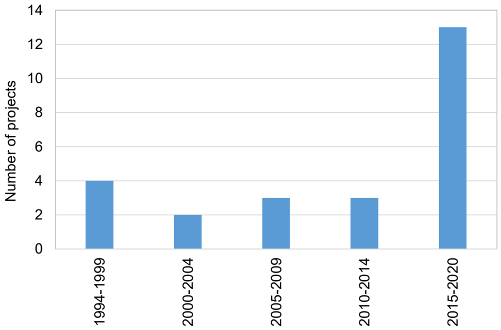
<Number of projects for various vehicle type, and development stages>





<Average surface area for PV, and trends in passenger car-based PV-powered vehicles>





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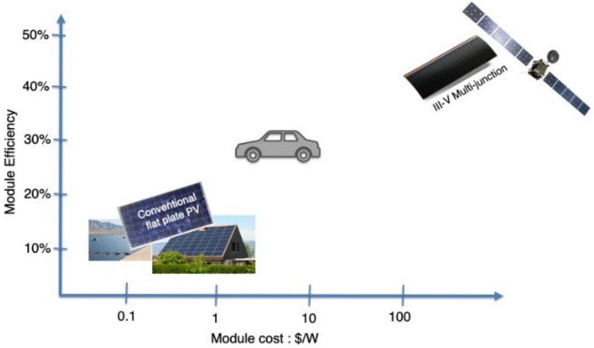
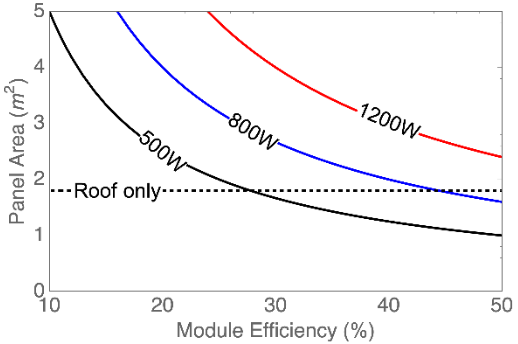
PV technologies for PV-powered vehicles

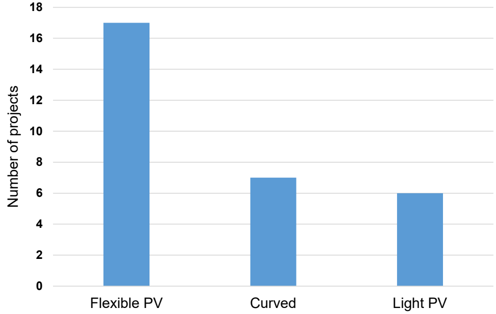
VIPV market: technologies that can attain premium efficiencies with costs in the range 1-10 USD/W. Among the existing technologies, flexibles are attractive from viewpoints of weight and efficiency.

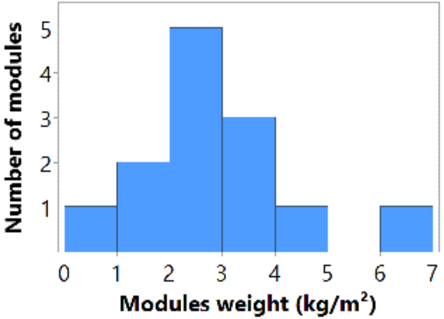
<Expected module cost, and relationship between PV module area and efficiency>

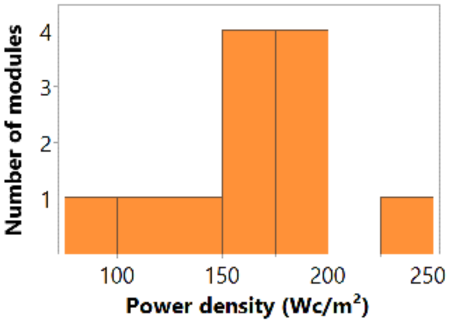




<Number of projects available for PV-powered vehicles, and characteristics of flexible PV>







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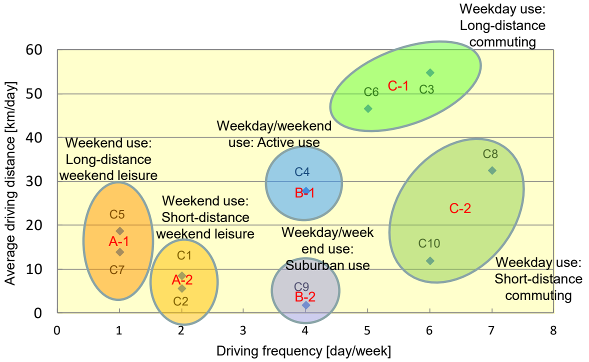
Case study on PV-powered passenger cars: Japan

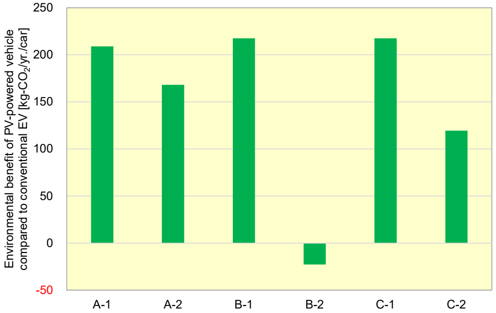
PV-powered vehicle would produce environmental benefit and reduce charging frequency. In case of shorter driving distance, the PV-powered vehicle will be free from electricity charging at the station. However, 1 kW PV might be an excess capacity for the shortest driving distance.

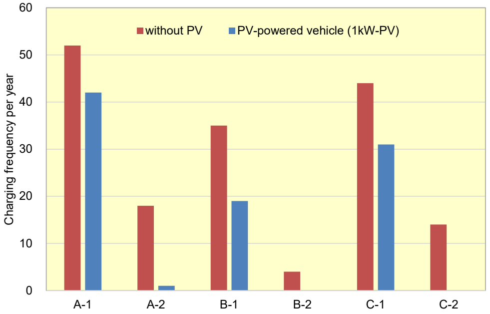
<Main assumptions, and driving patterns used in the analysis>

PV capacity for vehicle : 1 kWp
Effective PV elec. for driving: 653 kWh_{-DC}/kW/year
CO2 emission for PV : 1 008 kg-CO_2/kW
Battery capacity : 40 kWh
Vehicle efficiency : 8,33 km/kWh_{-AC}
Lifetime of vehicle : 12 years
CO2 emission of grid charging: 0,462 kg-CO_2/kWh



<Expected environmental benefit (CO_2 reduction) and frequency of electricity charging of PV-powered vehicle, compared to conventional electric vehicle>





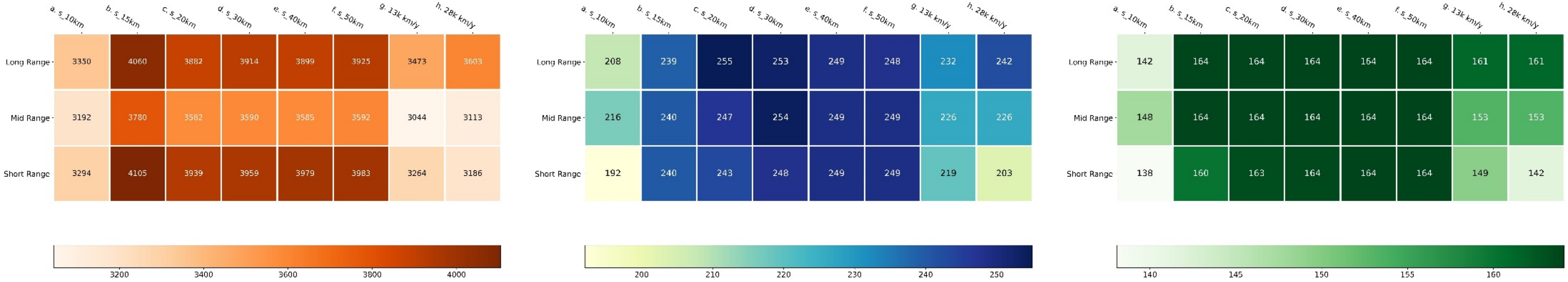
Case study on PV-powered passenger cars: the Netherlands

PV can supply energy for 3 000 – 4 100 km/year with an average of approximately 3 650km.
The net CO_2 savings are between 192 and 255 kg-CO_2/year/car across the profiles and vehicles.
The cost savings are between 138 and 164 EUR/year/car, although not considering the cost for PV.

<Main assumptions>

PV capacity for vehicle : 800 Wp
CO2 emission for PV : 1 229,16 kg-CO_2/kW
Lifetime of vehicle : 12 years
Electricity price (household): 0,221 EUR/kWh
Annual horizontal irradiance : 999,6 kWh/m_2/year
Energy consumption: long-/mid-/short range: 158/170/167 Wh/km
CO2 emission of grid charging : 0,437 kg-CO_2/kWh

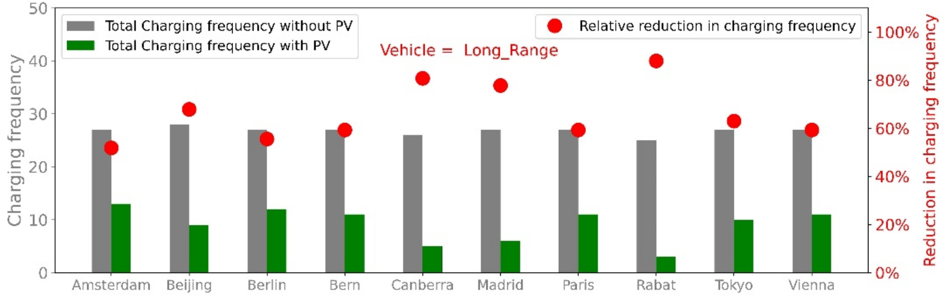
<Driving distance (km), CO_2-saving (kg) and cost saving for charging (EUR), per year in Amsterdam>



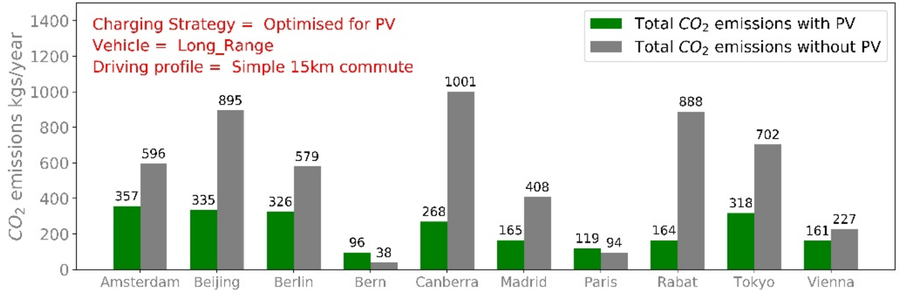
Potential benefits of PV-powered passenger vehicles

Preliminary analysis on potential benefits of PV-powered passenger vehicles in Task17 participating countries.

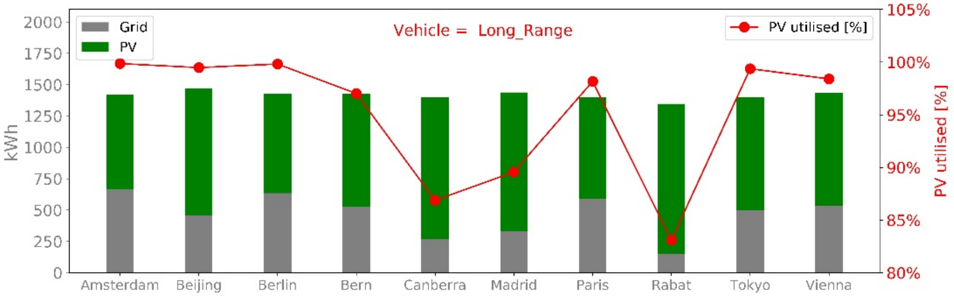
<Total charging frequency and the relative reduction for the Simple 15km commute profile>



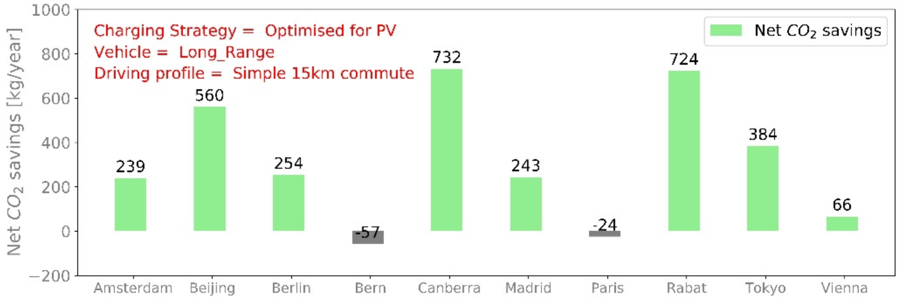
<Net CO_2 savings per location for the Simple 15km commute driving profile>



<Total electricity for driving divided into Grid and PV, and ratios of PV energy utilised>



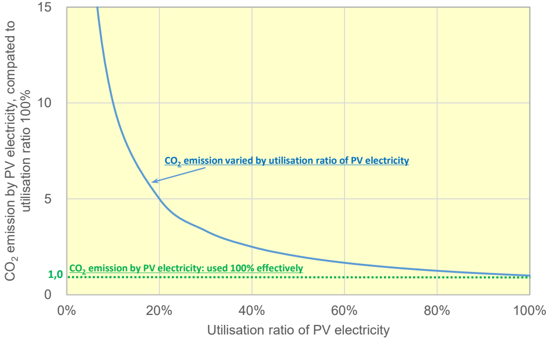
< Net CO_2 savings per location for the Simple 15km commute driving profile >

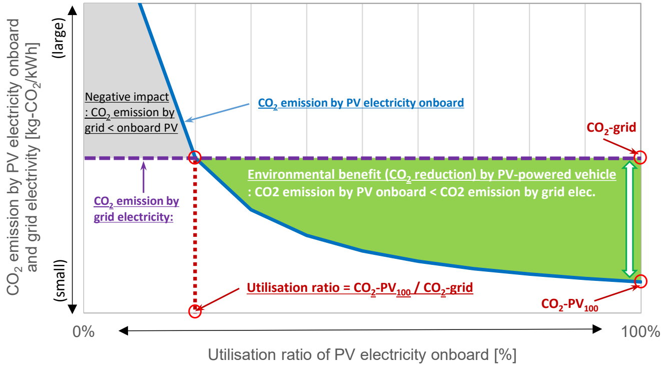


Impacts of PV utilization ratio on potential benefits

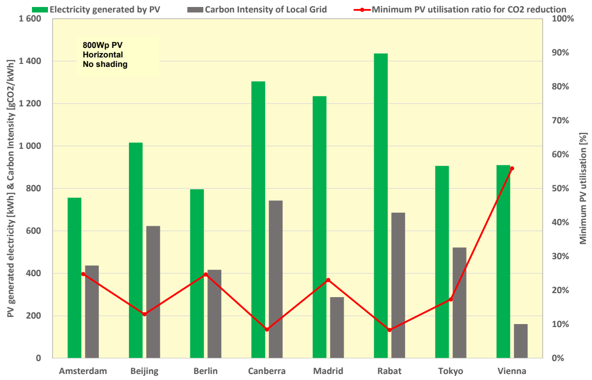
Potential benefits of PV-powered vehicles depend on the PV utilization ratio.

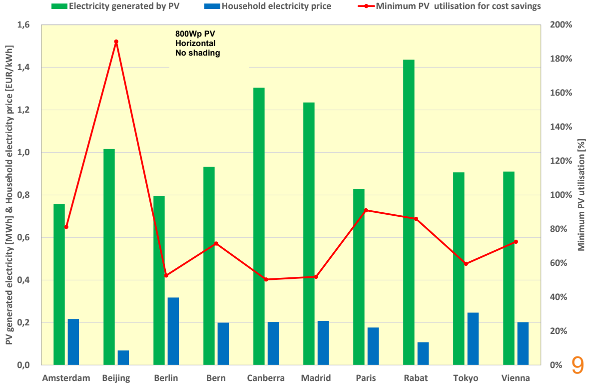
<Relations between CO_2 emission of PV/grid electricity, utilisation ratio of PV electricity, and CO_2 reduction by PV-powered vehicle>





<Minimum utilisation ratio of PV electricity to achieve a CO_2 reduction and a cost saving>





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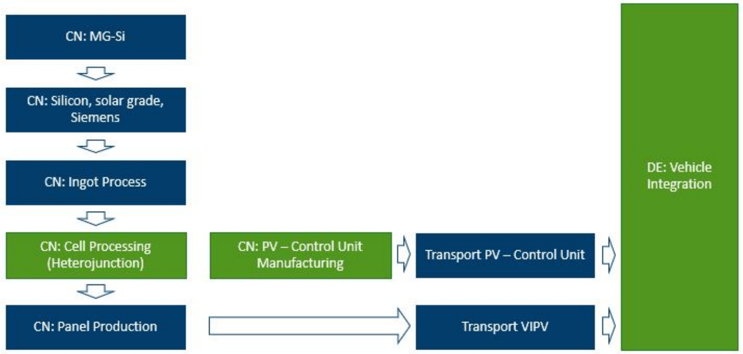
Case study on PV-powered light commercial vehicle: Germany

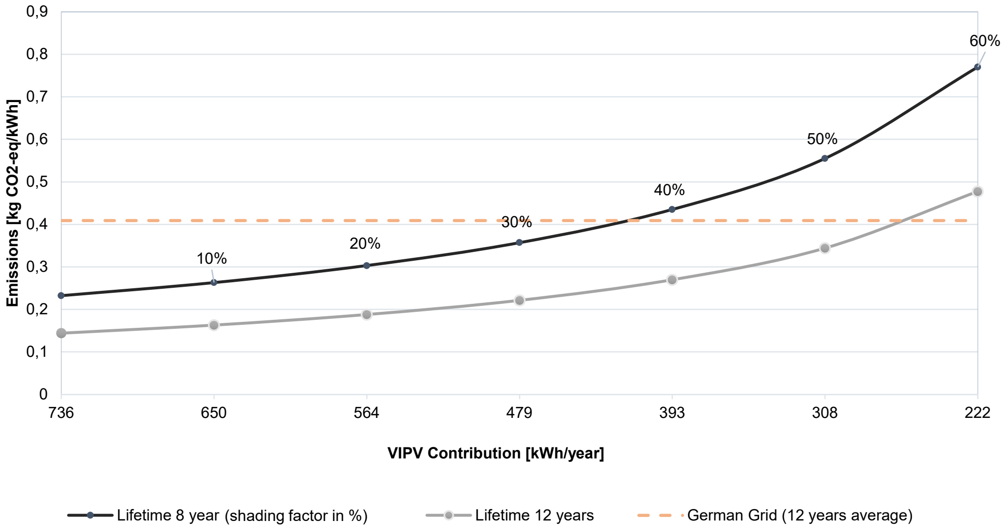
PV-powered vehicle can improve the carbon footprint for the reference case of an average shading factor (loss) of 30 % and 8 years of operation time: 0,357 kg CO_2-eq/kWh in reference case. Increased shading factor results in larger emission, but longer lifetime contributes to reduction.

<Main assumptions, and value chain assumed>

PV capacity for vehicle	: 930 Wp
Efficiency	: 19,7 %
Degradation	: 0,7 %/year
Operation lifetime	: 8 years
Location	: Cologne [N 50,938]
Performance ratio	: 0,805
Shadowing factor	: 70 %



<CO_2 emissions considering shading factor and prolonged >



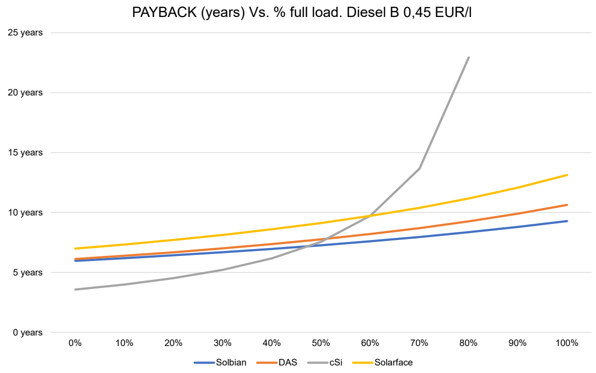
Case study on PV-powered reefer trucks: Spain

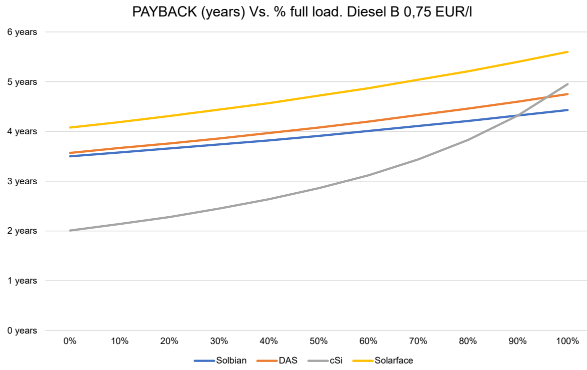
Fuel consumption for refrigeration of reefer trucks can be substituted by PV electricity.
The weight of PV system will have an impact on fuel consumption and possible load for delivery.
Cost payback time will depend on fuel/diesel price and % of time for full-loaded.

<Main assumptions>

Available area for PV
: 32,5 m^2 (maximum)
PV module efficiency and power
: 16,5 – 20,0 %, and 3,96 – 4,8 kWp
CAPEX for PV
: 3 500 – 7 000 EUR
Usage of PV electricity
: 81,1 % for refrigeration directly
: 11,9 % stored in battery with 20% losses
Diesel price for refrigeration
: 0,45 EUR/liter
Diesel price for ICE
: 0,75 EUR/liter
Conversion factor for refrigeration
: 2,96 kWh/1 liter
Conversion factor for ICE
: 0,9 kWh/1 liter

<Expected payback time for using PV>





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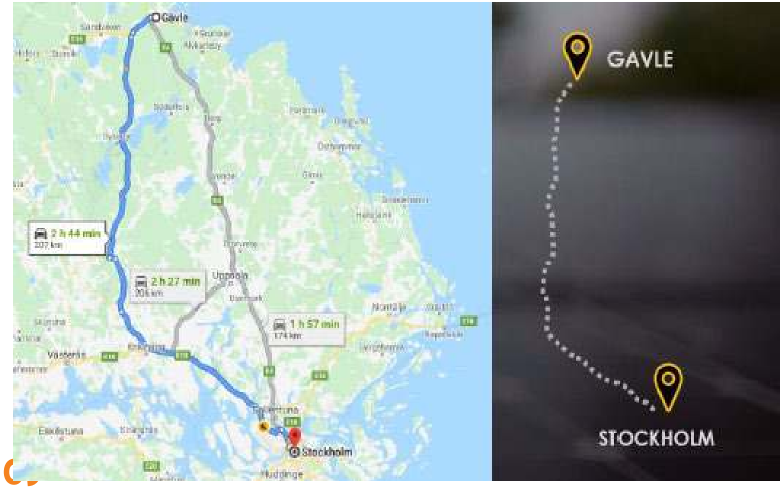
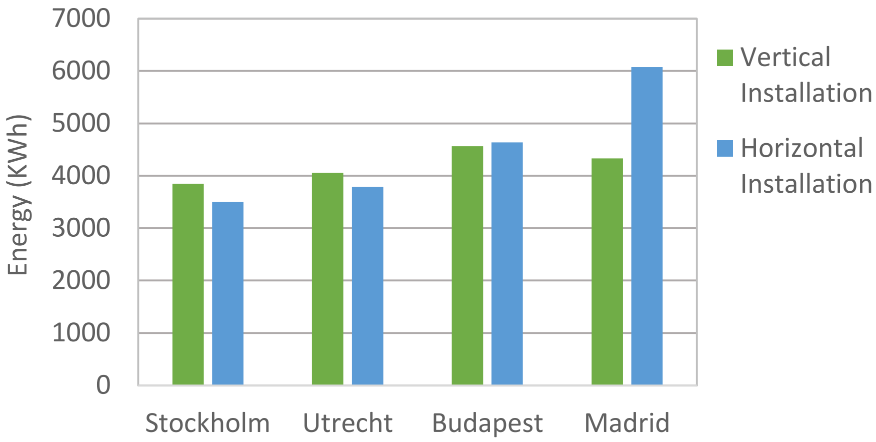
Case study on PV-powered truck trailers: the Netherlands

Two vertically oriented PV panels attached to the sides of a semi-trailer results in as much energy per year as a horizontally aligned PV module of the same size on top. In the lower the latitude, such as Spain, the horizontally oriented solar PV panel outperforms the two vertical ones.

<Example of driving route in Sweden, for simulation>



<Preliminary results of annual PV electricity production in some cities in Europe>



solar irradiance measurements

Solar irradiance measurement methods of TNO in the Netherlands, ISFH in Germany, University of Miyazaki in Japan, Bern University of Applied Sciences in Switzerland and UNSW in Australia.

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

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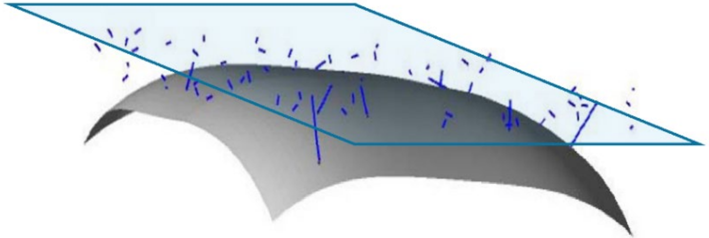
Discussions for standardisation of solar irradiation and module design

Several open-access works of literature have been published by testing engineers and scientists.

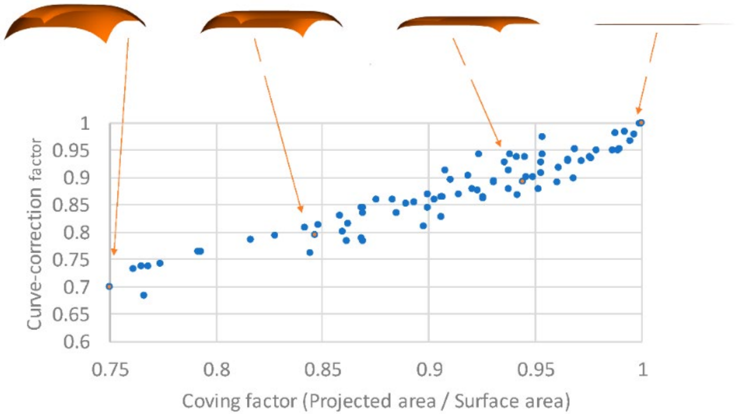
<Potential standardisation items discussed among scientists and testing engineers>

Rating test	Standard solar irradiation for standard testing condition
	Testing facility
	Curved surface
	Robustness to partial shading
	Robustness to dynamic shading
Design qualification	Standardization body
	Environmental test
	Requirements for qualification
Power Modeling	Simplified parameters
	Modeling by rigorous calculation
	Interaction to the string orientation
	Outdoor measurement validation
	Parameter measurement for modeling
	Solar modeling for vehicle
Energy Prediction	Difference between GHI and car-roof irradiance
	Energy Nowcasting
	Standard Smart Administration

<Discussions on curve correction factors>



(Geometrical relation between the curved PV panel (curved detector) and light source (corresponding to the projected area))



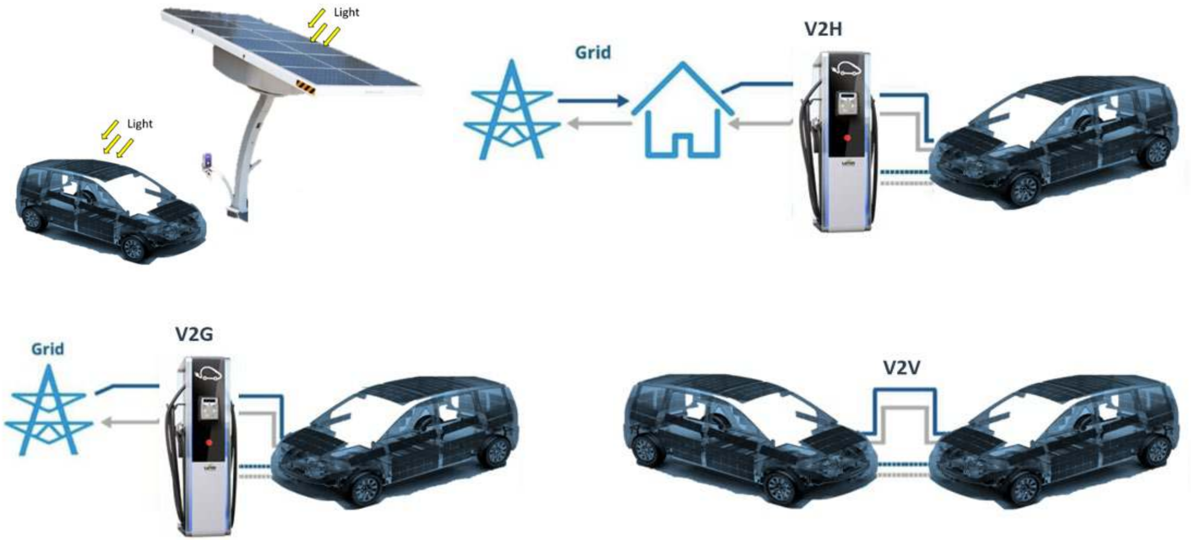
PV-powered vehicles combined with charging infrastructure

PV-powered vehicles may present maximum PV benefits while park outside the shade of PV-powered charging station.
PV electricity produced and stored by PV-powered vehicles can be used as additional flow of electricity during all the V2X services. However, the real “additional value” earned from PV-powered vehicles is the real-time production during the dwell time, on public parking or at home.

<SWOT for PV charging stations>

Strengths	Weaknesses
• Energy is produced locally, avoiding grid transmission losses • Reduced local grid overloading thanks to BESS if several EVs charge at the same time • Identical operation as regular charging points from user perspective	• Increased initial cost, particularly if local storage is considered • Requires upgrading existing electrical infrastructure with a bidirectional grid connection (V2G) • Insufficient PV power for EV fast charging
Opportunities	**Threats**
• Ability to use surplus PV production to meet energy demand from other local loads • Possibility to install grid-independent charging points if coupled with energy storage	• Lack of space for new charging stations from existing ones • Difficulty to place PV panels in an urban environment

<PV canopy infrastructure and principle schemes for V2X>



The way forward

PV-powered vehicles may offer significant benefits to drivers and 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 electric vehicles 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.

Currently, 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.

Thank you

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