Vehicle Integrated PV: State-of-the-Art and Expected Benefits

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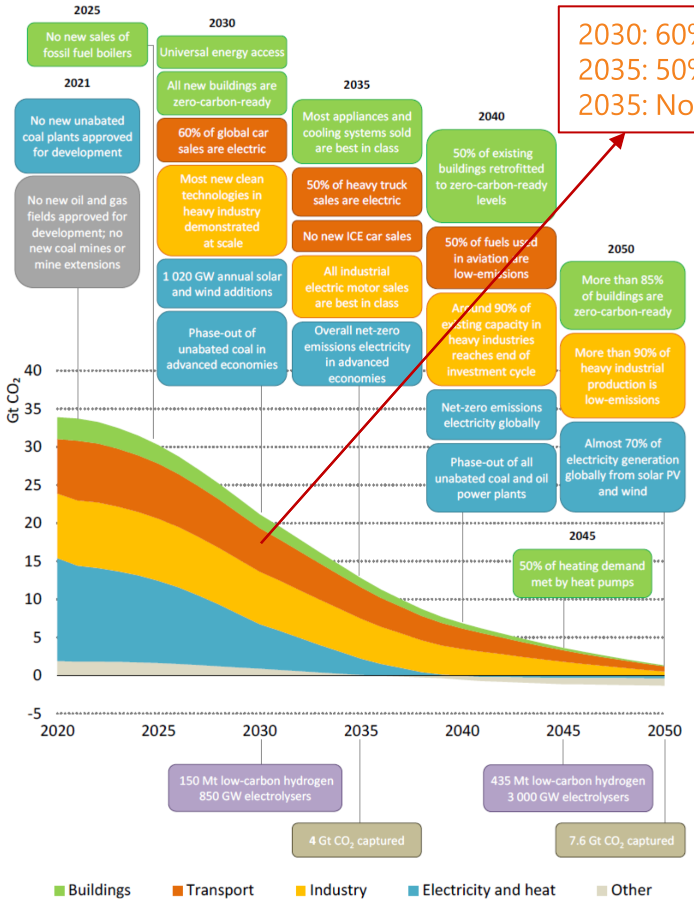
26 September 2022

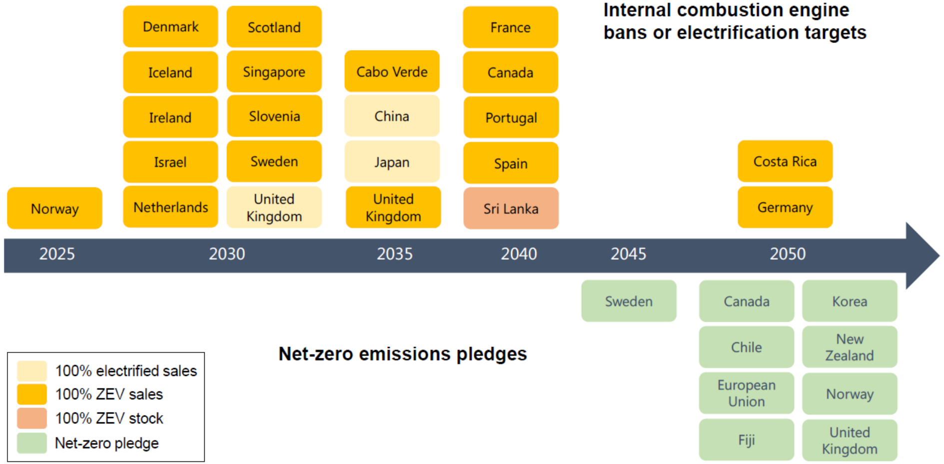
E-mobility for achieving net-zero society



Ref.) IEA: Net Zero by 2050, A Roadmap for the Global Energy Sector, 2021

2030: 60% of global car sales are electric
2035: 50% of heavy truck sales are electric
2035: No new ICE car sales

More than 20 countries have electrification targets or ICE bans for cars, and 8 countries plus the European Union have announced net-zero pledges



Ref.) IEA: Global EV Outlook 2021

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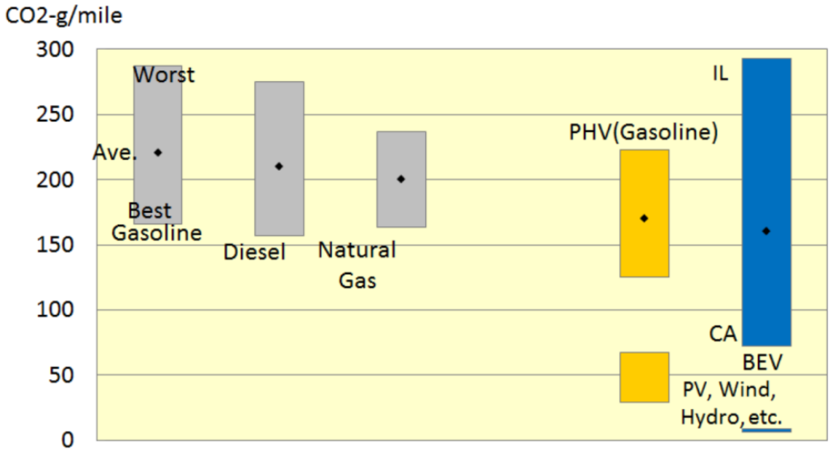
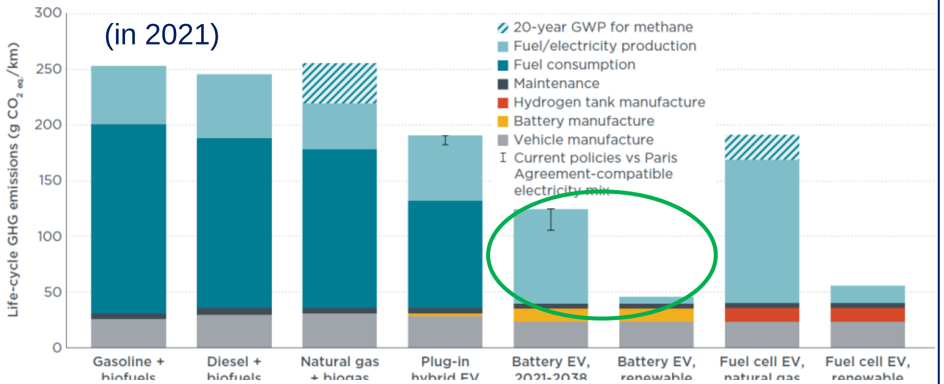
Electricity's 'Color' is an issue

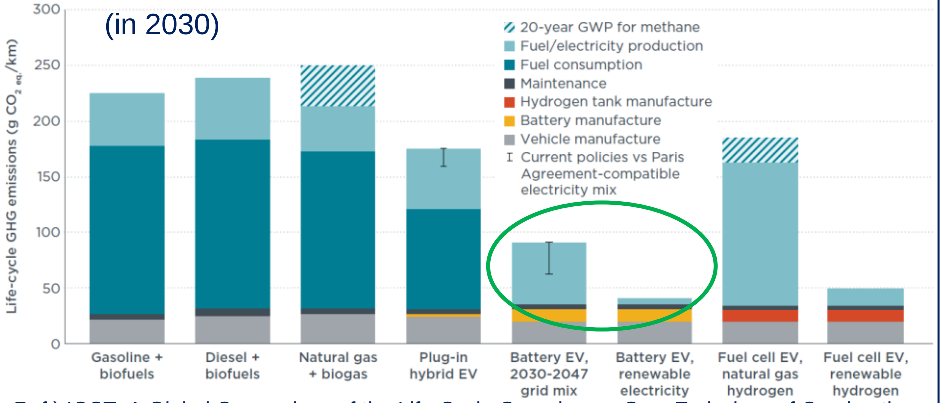
Well-to-Wheels Greenhouse Gas Emissions for 2035, Mid-Size Car



Ref.) U.S.DOE: Program Record (Offices of Bioenergy Technologies, Fuel Cell Technologies & Vehicle Technologies, 10 May 2013

Life-cycle GHG emissions of average medium-size gasoline, diesel, and CNG ICEVs, PHEVs, BEVs, and FCEVs registered in China, Europe, India, and the United States





Ref.) ICCT: A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars, October 2021

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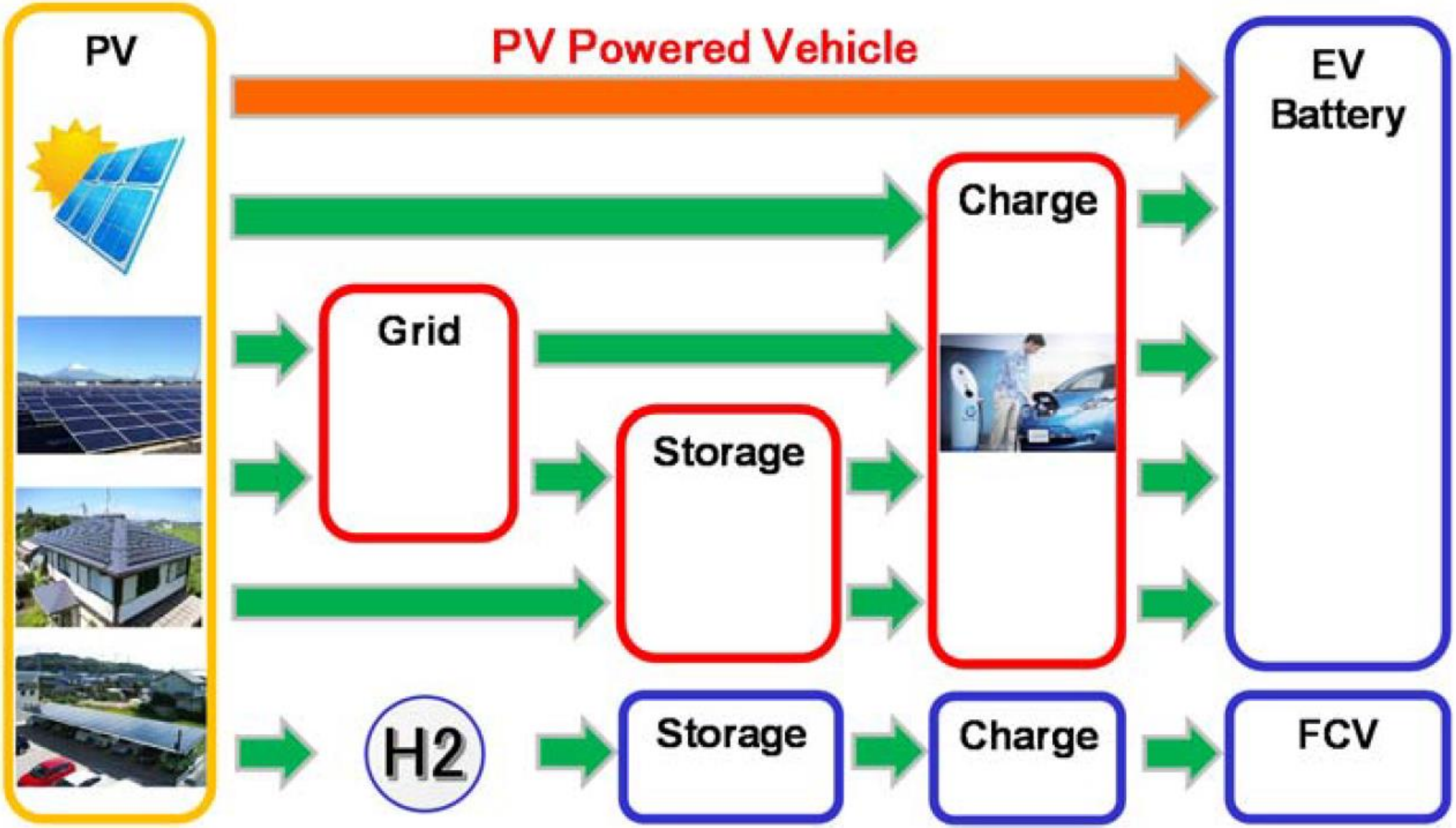
Possible electricity supply for vehicles



IEA PVPS Task17: PV and Transport

- **Goal**
  - Deploy PV usage in transport, which will contribute to reducing CO_2 emissions of the sector and enhancing PV market expansions
- **Participating countries**
  - Japan (Task manager), Australia, Austria, China, France (co-Task manager), Germany, Morocco, the Netherlands, Spain and Switzerland

Subtask 1: PV-Powered Vehicles
**Clarify the benefits and requirements for PV-powered vehicles and components*
**Identify barriers and solutions to satisfy the requirements*

Subtask 2: PV charging systems and PV power infrastructures
**Propose directions for deployment of PV equipped charging stations and PV power infrastructures*

Subtask 3: Potential contribution of PV in transport
**Estimate the potential contribution of PV in transport and propose milestones*

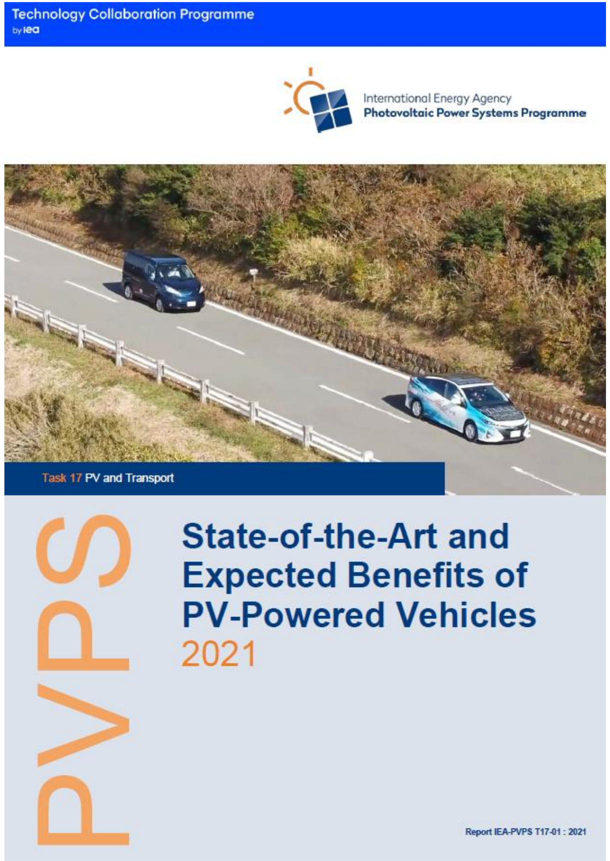
Subtask 4: Dissemination
**Accelerating communication and activities going ahead within stakeholders such as PV industry and transport industry*

PVPS Task17 Subtask1 report, released in 2021

- **State-of-the-Art and Expected Benefits of PV-Powered Vehicles**
  - ISBN: 978-3-907281-15-4
  - Available at the IEA PVPS website:

    https://iea-pvps.org/key-topics/state-of-the-art-and-expected-benefits-of-pv-powered-vehicles/

    https://iea-pvps.org/wp-content/uploads/2021/07/IEA_PVPS_T17_State-of-theart-and-expected-benefits-of-VIPV_report.pdf



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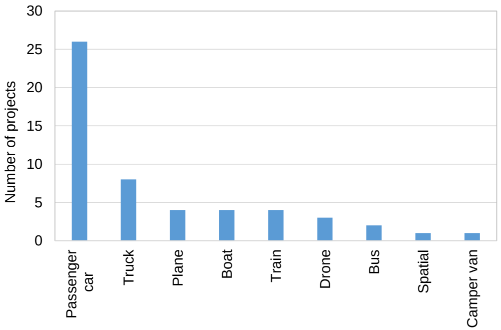
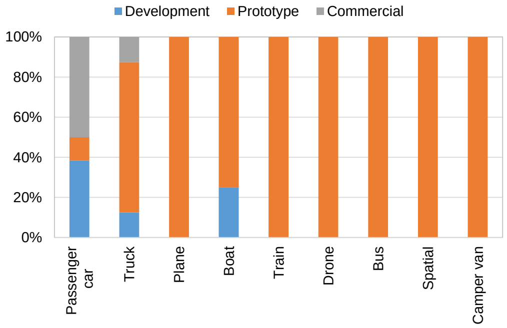
PVPS Task17 Subtask1 report: Table of contents

Trends in PV-powered vehicles development

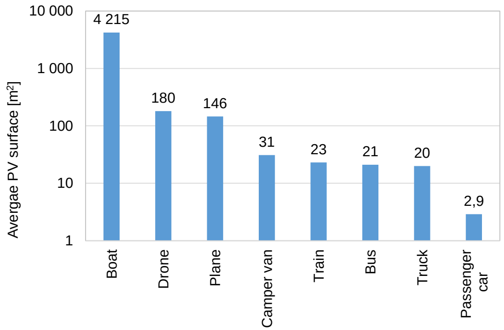
The majority of PV-powered vehicles development is passenger car-based projects.
Although expected available area for PV is small, the number of projects are rapidly increasing.

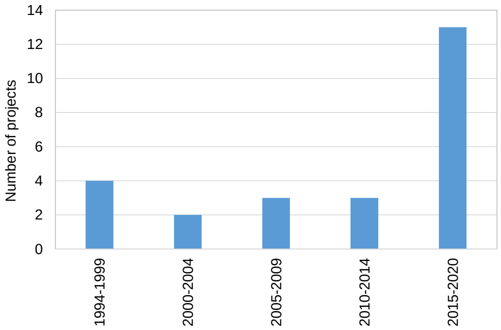
<Number of projects for various vehicle type, and development stages>





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





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PV-powered passenger cars fully covered by solar cells

Sion from Sono Motors

Lightyear One

Test car – Multijunction PV on Prius

Test car – Multijunction PV on e-NV200

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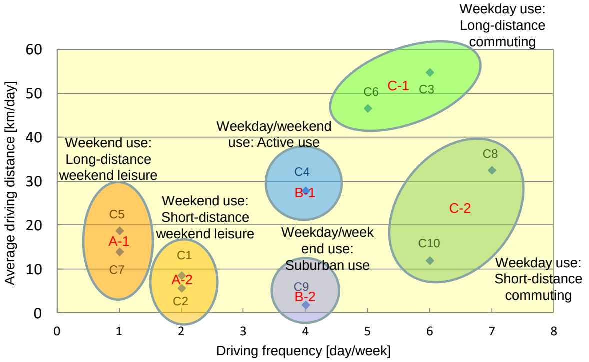
Case study on PV-powered passenger cars: Japan

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



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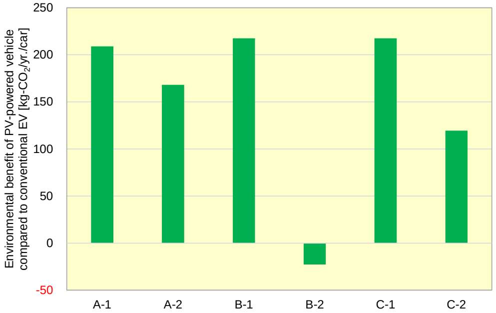
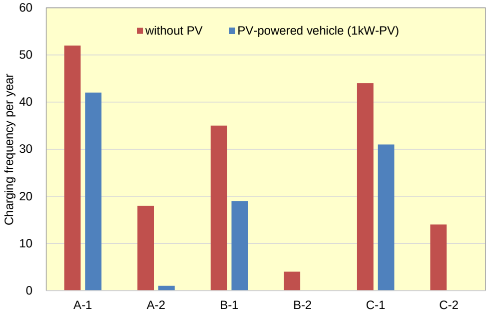
<Expected environmental benefit (CO_2 reduction) and frequency of electricity charging of PV-powered vehicle, compared to conventional electric vehicle>





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>

Driving distance (km):

	a. s_10km	b. s_15km	c. s_20km	d. s_30km	e. s_40km	f. s_50km	g. 13k km/y	h. 28k km/y
Long Range	3350	4060	3882	3914	3899	3925	3473	3603
Mid Range	3192	3780	3582	3590	3585	3592	3044	3113
Short Range	3294	4105	3939	3959	3979	3983	3264	3186

CO_2-saving (kg):

	a. s_10km	b. s_15km	c. s_20km	d. s_30km	e. s_40km	f. s_50km	g. 13k km/y	h. 28k km/y
Long Range	208	239	255	253	249	248	232	242
Mid Range	216	240	247	254	249	249	226	226
Short Range	192	240	243	248	249	249	219	203

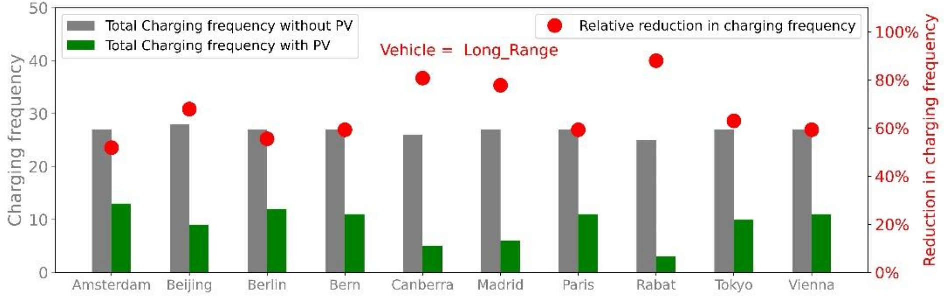
Cost saving for charging (EUR):

	a. s_10km	b. s_15km	c. s_20km	d. s_30km	e. s_40km	f. s_50km	g. 13k km/y	h. 28k km/y
Long Range	142	164	164	164	164	164	161	161
Mid Range	148	164	164	164	164	164	153	153
Short Range	138	160	163	164	164	164	149	142

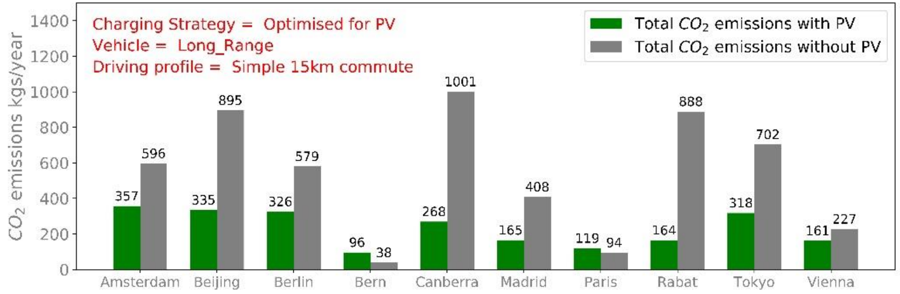
Potential benefits of PV-powered passenger vehicles

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

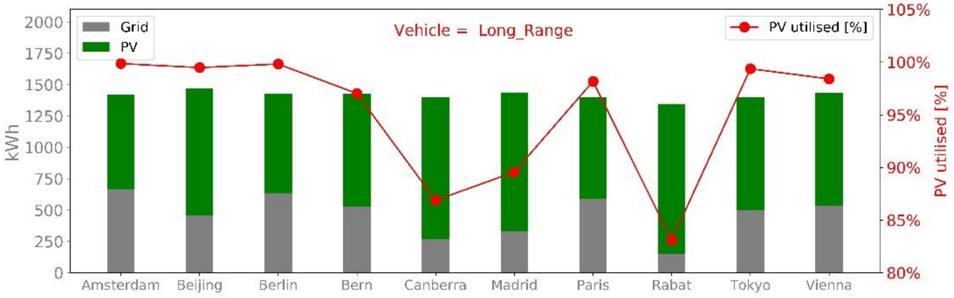
<Total charging frequency and the relative reduction for the Simple 15km commute profile>



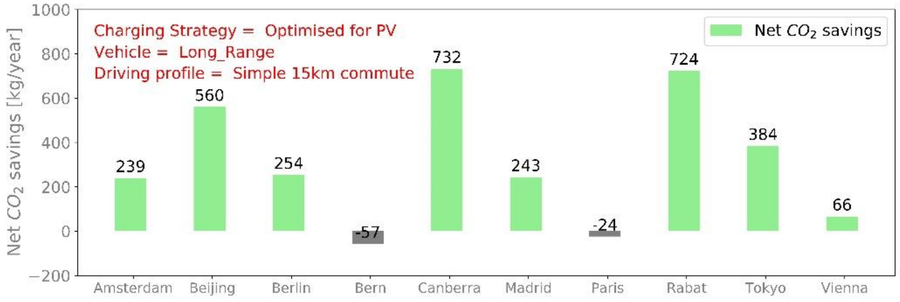
<Net CO_2 savings per location for the Simple 15km commute driving profile>



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

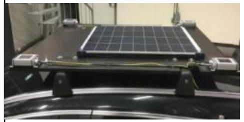
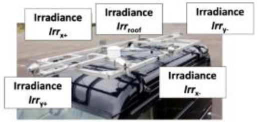


< Net CO_2 savings per location for the Simple 15km commute driving profile >



Vehicle 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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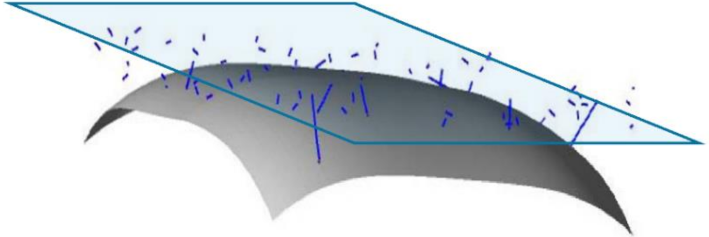
Discussions for standardisation of solar irradiation and module design

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

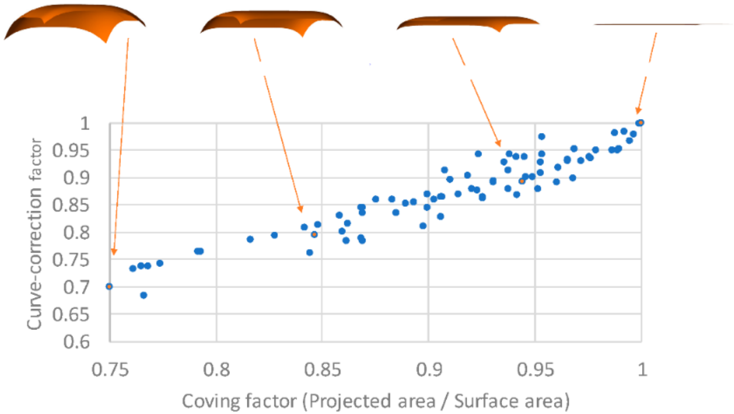
<Potential standardisation items discussed among scientists and testing engineers>

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))



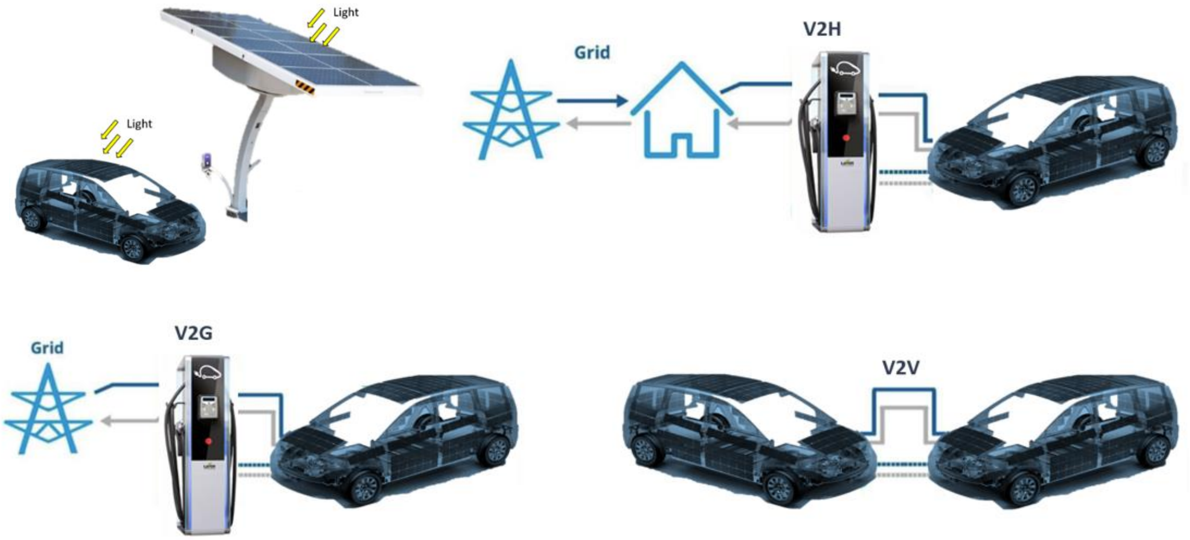
PV-powered vehicles combined with charging infrastructure

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>



Expected benefits of PV-powered vehicles

Feasible vehicle applications today

- Ultralight and highly efficient EVs
- Short range commuter vehicles
- Reefer trucks
- Light commercial vehicles
- PV-powered auxiliaries

PV cell/module technology state of the art and roadmap

- III-V multi-junction solar cells (30% efficiency, high efficiency moderate cost zone)
- Roof only requires 25% efficiency; including bonnet: 20%
- 500 Wp is a practical minimum = ~15 km/day
- Coloured VIPV will offer better aesthetics and is possible with little efficiency loss.
- Substrate modules with semiconductor material deposited directly onto metal or glass surfaces
- Perovskite cells: high efficiency, low cost and flexibility
- PV with longer lifetime, higher efficiencies, lower embedded emissions
- Need for tools and forecast methods, irradiance measurements

Expected benefits of PV-powered vehicles

Market outlook

- PV-powered vehicle is a promising and compelling solution for passenger and transport vehicles.
- Two types of vehicles stand out to benefit from VIPV: lightweight, efficient vehicles and short distance commuting vehicles. For the former, the additional range is quite important as the vehicle uses little energy per km; for the latter, solar can often provide all the electricity needed for the short commute.
- Electric transport is a new and promising market for PV deployment.
- Countries with less well developed grid and charging infrastructure seem interesting markets as well.

Practical benefits

- PV-powered vehicle can offer thousands of km/year of free “solar” range, and is the most direct way to drive using renewable energy.
- PV electricity generated on-board can be used directly or stored in the EV battery.
- On short commuting distances, PV-powered vehicle will increase the autonomy and independence of the driver (a decreased charging frequency of 10% to 60% compared to an EV).
- It makes it possible to use auxiliaries like the AC or ventilation without draining the battery

Expected benefits of PV-powered vehicles

Environmental benefits

- Environmental benefits are most favorable in countries with a high carbon intensity electricity mix and high solar irradiance.
- Studies in Japan and the Netherlands: up to ~250 kg-CO_2 savings per year for passenger cars.
- For countries with a low carbon intensity electricity, PV-powered vehicle provides a REN solution for future mixes.
- There may be a potential for slightly smaller battery capacities in EVs equipped with PV on-board.

Economic benefits

- Study in the Netherlands: electricity gross savings of up to 164 EUR/year for passenger cars.
- PV generated electricity can be used in buildings (V2H/V2X), which will further increase the PV utilization ratio.
- Study in Spain: for reefer trucks, the best estimate of payback time: 3.62 years.
- Solar on top to power auxiliaries can save 5% of total diesel consumption/year.
- The business case is better for trucks that are charged at maximum volume.

Task17 workplan for 2022-2024

Subtask 1: Benefits and requirements for PV-powered vehicles

Activity 1.1: Overview and recognition of current status of PV-powered vehicles

Activity 1.2: PV-powered passenger cars

: Technical requirements for VIPV, Possible contributions and benefits of PV-powered passenger

Activity 1.3: PV-powered light commercial vehicles

Activity 1.4: PV-powered heavy duty vehicles

Subtask 2: PV-powered applications for electric systems and infrastructures

Activity 2.1: Overview and recognition of current status of PV-powered for EV charging infrastructure

Activity 2.2: Requirements, barriers and solutions for PV-powered infrastructure for EV charging

Activity 2.3: Possible new services associated with the PV-powered infrastructure for EVs charging (V2G, V2H)

Activity 2.4: Societal impact and social acceptance for PV-powered infrastructure for EVs charging and new services

Subtask 3: Potential contribution of PV in transport

Activity 3.1: Resilience by PV and vehicles

Activity 3.2: Business models and market diffusion of VIPV/ VAPV

Activity 3.3: Possible contributions and deployment scenarios for ‘PV and Transport’

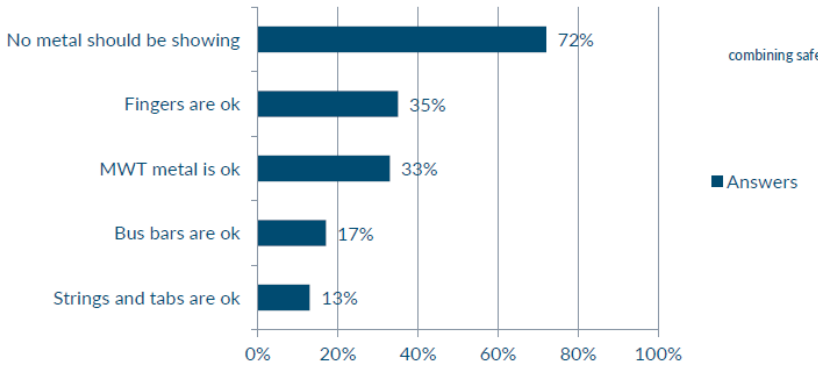
Subtask 4: Dissemination

Recent topics on VIPV

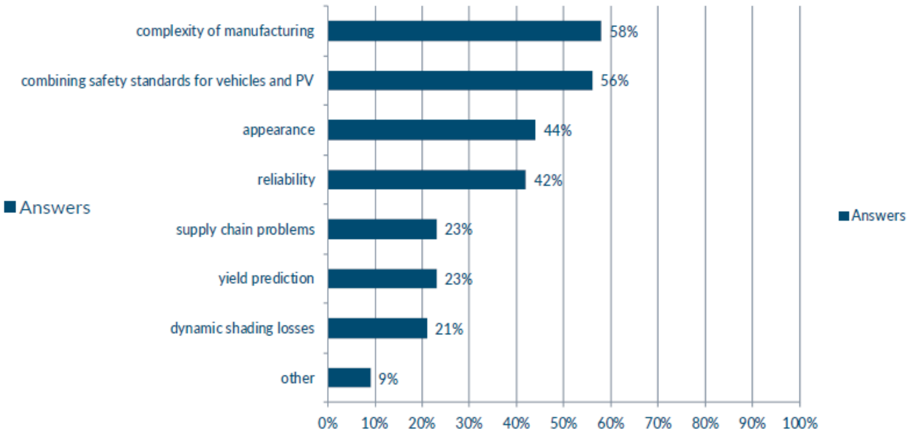
TNO SURVEY OF THE VIPV WORLD

RESULTS TO BE PRESENTED AT PVSEC-33 NAGOYA NOVEMBER 2022

- Appearance:
  - How much metal can be visible from the front



- Technical Bottlenecks
  - What are the biggest bottlenecks to large scale rollout of VIPV?



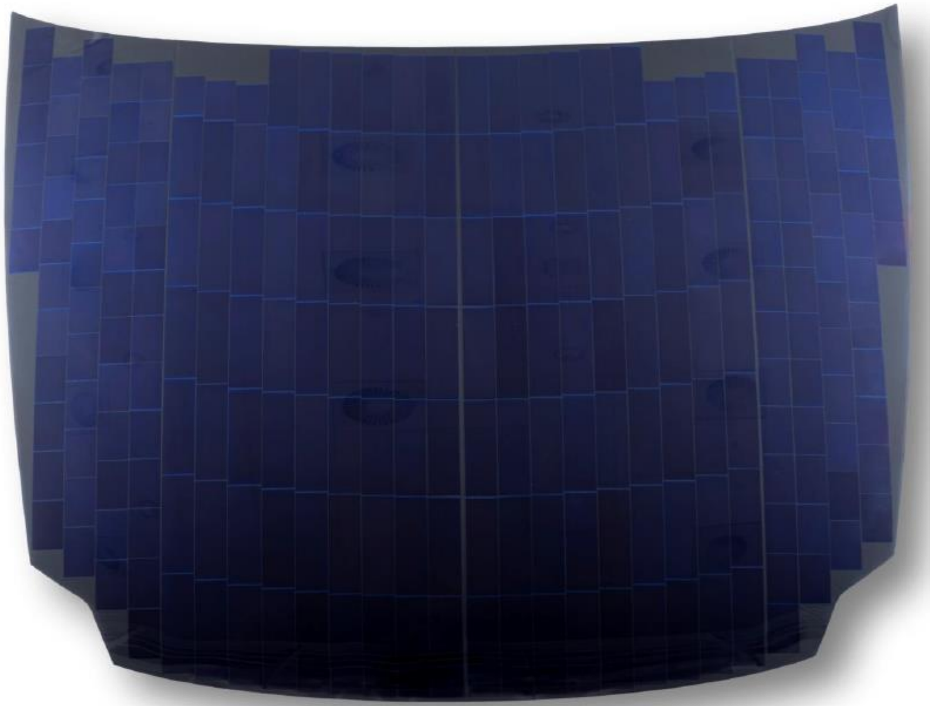
Recent topics on VIPV

TNO PROTOTYPING NEW TECHNOLOGY

- TNO works on new technology to increase the coverage fraction
- Maintain good aesthetics
- Simpler manufacturing processes

Reference:

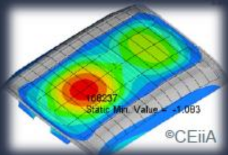
V. Rosca, N. Guillevin, L. Okel, B.K. Newman, Prefab approach to mass customization of integrated PV. SiliconPV 2022

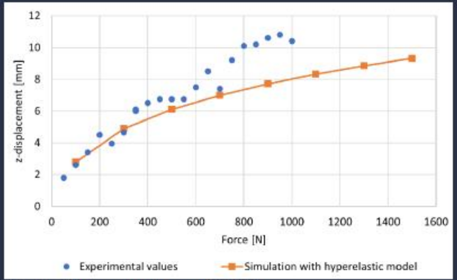


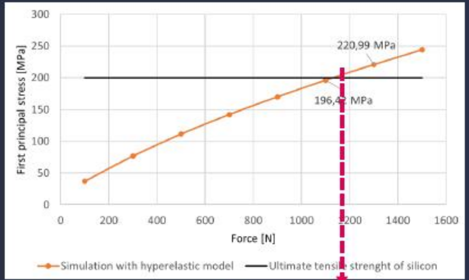
Recent topics on VIPV

Photovoltaic for Automotive Application - What are the limitations?

Validation of maximal Stress on the PV parts



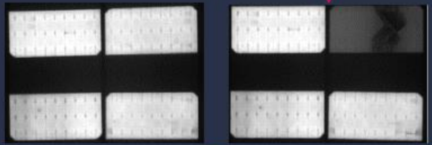




Yeoh's hyperelastic model [1]:

$$W = \sum_{i=1}^{3} C_i \cdot (\lambda^2 + \frac{2}{\lambda} - 3)^i$$

With C1= $2.97 \cdot 10^8$, C2= $-7.75 \cdot 10^9$ and C3=$1.32 \cdot 10^{11}$



Good fit between calculated ultimate tensile stress in c-Si and cell breakage observation

[1] O. H. Yeoh, "Some forms of the strain energy function for rubber," Rubber Chemistry and technology, vol. 66, no. 5, pp. 754–771, 1993.

csem Simoldes Plastics CEiiA PVAB PhotoVoltaic Automotive Body COMPETE 2020 PORTUGAL 2020 UNIÃO EUROPEIA Fundo Europeu de Desenvolvimento Regional

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Bundesamt für Energie BFE
Office fédéral de l'énergie OFEN

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Recent topics on VIPV

SOLARIZATION KIT FOR VIPV: CONCEPT AND BENEFITS

- **Solarization kit to retrofit electrical vehicles** in after-sales
  - Range extension (800 km/year estimated in France)
  - Gain in comfort by decreasing the frequency of recharging (-14% expected)
  - Reduction in the vehicle's CO_2 impact over its entire life
- **Main technical challenges**:
  - Interface directly to the vehicle's traction battery, with minimal energy losses between the PV module and the energy use
  - Ease and reversible installation
  - Compatibility with all types of electric vehicles
- **Our field demonstrator:**
  - Conformable and light-weight PV module of 145 Wp for any metallic body (patented)
  - Connection to battery with the stored energy is injected into the grid
  - System designed to be non-intrusive to the vehicle
- **First conclusion:**
  - Autonomy gain of 5 km/day on a sunny day demonstrated.

Global view of the Renault Zoe vehicle with the 145 Wp module produced and installed at INES.

Conformable and light-weight PV module of 145 Wp

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Call for Presentations currently open until 16 October

Topics:

- PV Cell & Module Technology
- Vehicle Technology (with or without PV)
- System Energy Management
- Safety & Reliability
- Performance & Costs
- Production & Implementation
- Environmental & Social Impact

www.pvinmotion-conference.com

Thank you

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