SolarMoves

Final report

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List of abbreviations and Definitions

AC: alternate current

AFIR: alternative fuels infrastructure regulation

BEV: Battery Electrical Vehicle

Bidirectional Charging: Ability for a vehicle to both receive and transmit energy to the grid or micro-grid system

BigEye: PV system simulation tool by TNO.

BMS: Battery Management System

CAPEX: Capital Expenditures

CEO: Chief Executive Officer

CESF: Clear sky Energy weighted Shading Factor

CLS: Clear sky

CO_2: Carbon dioxide

CPO: Charging Point Operator

DC: Direct current

DC: Direct current

Driving Profile: Time series data containing time and geolocation describing a specific movement in time and space for predefined use cases

DWD: Deutscher Wetterdienst

EAB: Executive Advisory Board

EFM: Energy Flow Model. The EFM is used to analyse the electrical energy flows in an electrical vehicle

ESF: Energy weighted Shading Factor

EU: European Union

EU27: 27 countries of the European Union

EV: Electric vehicle

External Vehicle Efficiency: electricity consumption per kilometre of a vehicle, measured at the charging plug. Onboard electricity generation is included (including PV)

GHG: Green House Gas

GHI: Global Horizontal Irradiation is the total amount of solar radiation received from above by a horizontal surface. It includes both Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DIF).

GIS: Geographic Information system

GNSS: Global Navigation Satellite System

GPS: Global Positioning System

Gross Energy Consumption: Referred to the energy consumption of the vehicle, excluding the benefits of the onboard solar system. In the Lightyear 0 measurement campaign, this is used to show the vehicle consumption of all system during driving, excluding the benefit of the solar system during this time.

HDV: Heavy-Duty Vehicles: freight vehicles of more than 3.5 tonnes (lorries) or passenger transport vehicles of more than 8 seats (buses and coaches)

HV: high voltage

ICE: Internal Combustion Engine

Internal Vehicle Efficiency: electricity consumption per kilometre of a vehicle, measured as the net difference in state of charge of the battery/batteries. Onboard generation and charging losses are excluded.

ISE: Institute for Solar Energy Systems, a department of Fraunhofer-Gesellschaft and project partner

KNMI: Royal Netherlands Meteorological Institute

LCZ: Local Climate Zone

LDV: Light-Duty Vehicle(s): passenger cars and vans

LV: low voltage

MEO: Mobility Energy Optimization model

OEM: Original Equipment Manufacturer

OPEX: Operating Expenditures

PTC: positive-temperature-coefficient

PV on all surfaces: PV on sun-facing surfaces and PV on the sides (vertical) where possible and sensible

PV: Photovoltaics

PVlib: a community-developed toolbox that provides a set of functions and classes for simulating the performance of photovoltaic (PV) energy systems

RED III: Renewable Energy Directive III

RRMSE: relative root mean squared error

SoC: State of Charge

Solar Driving Profile: GHI (including shading) assigned to driving profiles (replaces the term “Solar Cadastre” in the technical offer)

SOMopy: Solar Moves Python

SoT: Solar on Top

TCO: Total Cost of Ownership

TEN-T: Trans-European Transport Network

TNO: Project partner. Netherlands Organisation for Applied Scientific Research

V1G / smart charging: Optimization algorithm that enables charging and/or discharging (in the case of bidirectional charging) decisions to be made when it is most beneficial to do so

V2G: Vehicle to Grid: Bi-directional charging, in which the electrical vehicle not only can take up power from the grid but can also deliver power to the grid

VCM: Value Case Methodology

VECTO: Vehicle Energy Consumption calculation Tool

Vehicle Archetype: a combination of a vehicle class or category with certain functional and physical properties and a use pattern or mission profile.

VIPV: Vehicle Integrated PV. VIPV designates the mechanical, electrical and design-technical integration of photovoltaic modules into vehicles. The PV modules blend seamlessly into the vehicle exterior and are connected to electric loads or the drive battery in electric vehicles

Executive Summary

Unlocking the Potential of Vehicle Integrated Photovoltaics (VIPV) for the European Transport Sector

Vehicle Integrated Photovoltaics (VIPV) is a mature technology ready for deployment on passenger cars, vans, buses, electric trucks, and retrofit on existing diesel truck/trailers. VIPV is not a total replacement for charging infrastructure needs, but it is a powerful **efficiency multiplier**. It reduces the strain on the electricity grid, lowers the total cost of transport for logistics companies, and offers autonomy of use and charging to private drivers. It delivers immediate CO2 benefits and causes less energy dependence. We are projecting that in some scenarios total VIPV production can be up to 27 TWh in 2030.

In addition to further cost decreases and technical integration challenges, wide deployment of VIPV can be also helped with a regulatory framework that can unlock a technology that turns millions of vehicles from pure energy consumers into mobile renewable energy power plants.

1. The Approach

The European Union's transition to zero-emission transport faces a critical bottleneck: the electricity grid. As millions of vehicles switch from fossil fuels to electric batteries, the demand for charging infrastructure and local grid capacity is projected to surge. **SolarMoves** investigates a decentralized solution to this challenge: **Vehicle Integrated Photovoltaics (VIPV)**. By integrating solar cells directly onto vehicle surfaces—roofs, hoods, and sides—vehicles can generate their own electricity, reducing reliance on the grid.

This report synthesizes findings from a multi-phase study combining computer modelling, real-world measurement campaigns, and economic analysis. The study's scientific rigor is grounded in the development of specific "vehicle archetypes" to model energy flows accurately across different use cases.

To ensure the results reflect the diverse reality of European transport, the project was structured into three core activities:

1. **Modelling & Simulation:** A complete model was built from individual vehicle to fleet level to analyse the impact of VIPV on the European transport ecosystem, now and in the future. Assessing energy demand and solar yield for 23 specific "vehicle archetypes" across two climate zones. These results were used to simulate vehicle and fleet level impacts.
2. **Real-World Measurement Campaign:** Deployment of irradiance sensors on a fleet of trucks, vans, passenger cars, and buses creates a massive database of real-world measurements of solar irradiance and availability on roads throughout Europe. In addition, three selected vehicles equipped with VIPV systems (a car, a van, and a truck) were used in controlled case studies to create a database of real-world VIPV use cases. The data from both models was used to validate the modelling against real-world conditions, including on-board energy use, shading and weather conditions.

3. **Value Case & Policy:** A Total Cost of Ownership (TCO) analysis and stakeholder interviews were used to determine economic and market potential and viability, generating a set of policy advice that could accelerate the adoption of VIPV.

Methodology: The 23 Vehicle Archetypes

To ensure the results reflect the diverse reality of European transport, the consortium defined **23 distinct vehicle archetypes**. An archetype is a specific combination of a vehicle class (e.g., small car, heavy truck) and a usage pattern (e.g., urban commute, long-haul logistics).

These archetypes formed the basis of all simulations and measurements:

- **Passenger Cars (11 Profiles):** This category includes **5 profiles** for small cars (ranging from "occasional use" to "car sharing"), **3 profiles** for medium-sized cars, and **3 profiles** for SUVs, covering usage patterns from daily urban commuting to long-distance highway travel.
- **Vans (4 Profiles):** The study modelled **2 profiles** for small vans and **2 profiles** for large vans, distinguishing between local distribution (stopping frequently) and regional distribution logistics.
- **Buses (4 Profiles):** This includes **2 profiles** for low-floor buses (urban and peri-urban public transport) and **2 profiles** for high-floor coaches (regional transport and long-distance highway travel).
- **Trucks (4 Profiles):** The heavy-duty segment includes **2 profiles** for rigid trucks (urban and regional distribution) and **2 profiles** for tractor-trailers (regional and long-haul freight).

These archetypes were simulated in two distinct climate zones—**Amsterdam** (representing Central Europe) and **Madrid** (representing Southern Europe)—to assess the impact of solar irradiance on energy generation. From these detailed archetypes models, a representation of the total EU fleet both now and in the future to look at vehicle level and fleet level impacts.

2. Key Findings: Impact on Energy, Grid, and Cost

The study reveals that VIPV is a viable technology capable of significantly altering the energy profile of the European transport fleet. The results from the methodology and impact assessment and the validation phase highlight impacts across three levels: the vehicle, the fleet, and the electricity grid.

Vehicle Level: Reduced Energy Demand & Convenience

The integration of solar panels significantly reduces the external electricity required to charge EVs, with the impact varying by vehicle size and location.

Passenger Vehicles: In Southern Europe (Madrid), VIPV was found to contribute up to **50%** of the annual energy requirement for some passenger vehicle archetypes. In Central Europe (Amsterdam), this contribution is up to **35**% (Figure 12 and Figure 13).

- **Grid Consumption Drop:** For a small passenger car in Amsterdam, integrating solar panels reduced grid electricity consumption from **~160 Wh/km to less than 100 Wh/km** (Figure 20**).**

- **Convenience:** The reduction in charging events is substantial. For passenger cars, VIPV reduced the need for charging stops by **9–56% in Amsterdam** and **14–76% in Madrid**, depending on the season and the specific usage profile. For low-mileage urban users, , in the summertime this can translate to weeks of autonomy without plugging in.
- **Commercial Vehicles:** For vans, trucks, and buses, the energy demand from propulsion is extremely high, meaning solar generation contributes a smaller percentage of the total energy used but still leads to a huge amount of energy generated and directly delivered to the vehicle. Furthermore, for electric trucks, the analysis showed that VIPV could still reduce grid dependence and in that way have a positive impact on net congestion. As the primary benefits in this sector are often financial or operational (e.g. powering auxiliary cooling systems without idling) benefits need to be made clear. For distribution deliveries, cases and models show a potential range extension of up to 15% which in-turn was equivalent to 25-30% of the EV rigid truck's electrical needs excluding propulsion.

Fleet Level: Macro-Economic Energy Savings

When scaled to the entire EU fleet, the impact of VIPV is clear on energy security and greenhouse gas savings.

- **Energy Savings:** If VIPV and other vehicle energy efficiency measures are widely adopted, the EU could reduce total grid electricity demand by up to **27 TWh annually in 2030.** This is equivalent to the annual electricity consumption of a small European nation.
- **CO2 Reduction:** This reduction in grid demand translates directly to emissions savings. The study projects a potential reduction of **2.7 million tons (Mton) of CO2 equivalents** annually by 2030. Application of VIPV on the trailers of diesel trucks to power auxiliary systems could increase this by as much as 15–17 million tonnes of CO_2 annually.

Grid Level: Alleviating Congestion

One of the most critical findings concerns the local electricity grid. The widespread adoption of EVs threatens to overload neighbourhood transformers.

- **Infrastructure Savings:** The ubiquitous adoption of VIPV, especially when combined with smart charging technologies, could reduce the need for grid infrastructure investments by **20% to 25%**.
- **Peak Shaving:** In a scenario with high EV adoption (e.g., 80% of a neighbourhood driving electric), VIPV reduces peak demand. The simulation showed that VIPV effectively acts as a **25% increase in local transformer capacity**, mitigating the risk of blackouts during peak charging times.

Economic Reality: Total Cost of Ownership (TCO)

The financial case for VIPV varies significantly between vehicle types.

- **Passenger Cars:** Currently, the TCO for VIPV passenger cars is neutral or slightly negative compared to standard EVs due to the upfront cost of the solar technology. However, the "convenience value" of fewer charging stops is high.

- **Heavy-Duty Vehicles:** For commercial vehicles, the business case is stronger. For **ICE (diesel) trucks**, equipping them with solar to power auxiliary systems (like refrigeration) yields a payback period of **~1-2 years**. For **electric trucks**, the payback period is generally under 5 years, driven by energy charging savings and range extension.

3. Real-World Validation: Lessons from the Road

To validate the computer models and create and extensive set of data to be used in future studies, the consortium launched a massive data collection campaign (Task 2). Fleets of vehicles equipped with irradiance sensors travelled over **1.2 million kilometres** across Europe between March 2024 and September 2025.

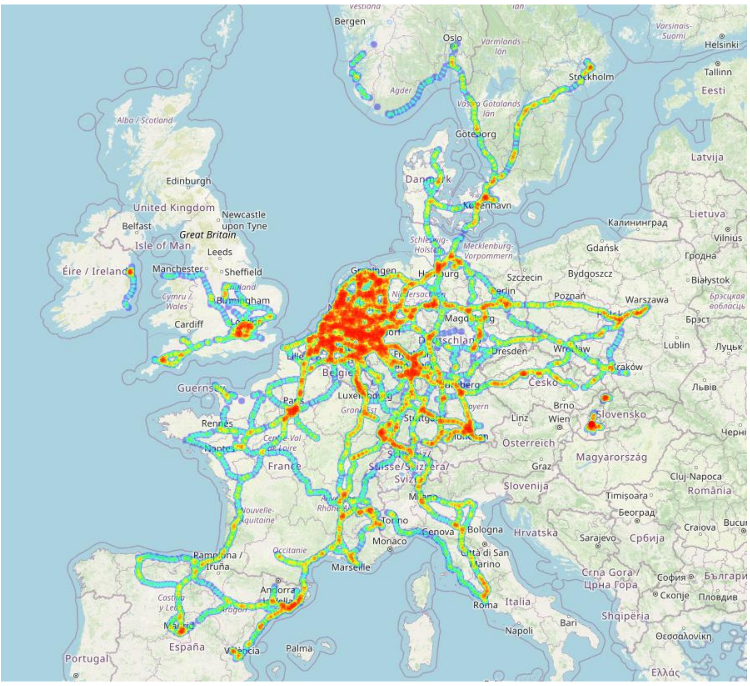


Figure 1: Heatmap of covered distances in Europe

The fleet included **eighteen vehicles including passenger vehicles, trucks, buses, and vans. These irradiance measurements are used to provide more detailed input for improved modelling of the available solar resource for mobile and distributed energy.**

In addition, 3 vehicles outfitted with VIPV systems, including a **Lightyear 0** (solar passenger car), **Ford E-Transit** (electric van), and a long-haul delivery truck/trailer (diesel) were deployed in controlled circumstances to directly measure the impact of real VIPV systems.

Case Study Results

1. Lightyear 0 (Passenger Car)

- **Context:** Summer campaign in the Netherlands (20 days).
- **Result:** The vehicle generated **49.3 kWh** of solar energy, covering **~40%** of its total driven distance (1,186 km) purely on solar power.

- **Significance:** Even in moderate climates and with a high-milage driving profile, efficient passenger EVs can derive up to half their miles from the sun.

2. Ford E-Transit (Delivery Van)

- **Context:** Delivery route simulation in Northern Europe.
- **Result:** In summer (June), the solar system provided **~12.5%** of the vehicle's recharging needs, extending daily range by nearly **10 km**.
- **Significance:** VIPV provides critical range extensions for commercial delivery, reducing downtime.

3. Long-Haul Logistics Truck

- **Context:** Cross-European logistics.
- **Result:** Top-mounted sensors confirmed that trailers offer a massive surface area, which could generate up to 55 kWh/day of useable solar energy (with 20% panel efficiency and 30 sq. meters of area). This leads to a range extension of about 50 km for an electric truck-trailer combination. Utilizing both roof and sides could generate between 90 - 110 **kWh/day** in summer (Figure 96).
- **Significance:** This confirms the viability of "side-loading" solar as a major untapped energy source for the logistics sector.

4. Stakeholder Analysis: Costs and Benefits

The financial viability of VIPV varies by stakeholder and vehicle type. The **Total Cost of Ownership (TCO)** analysis for 2030 highlights where the economic case is strongest [See Source 623-637].

Table 1: Key Stakeholder Benefits and Costs (2030 Scenario)

Stakeholder	Key Benefit	Key Cost/Challenge	Verdict
Passenger Car Owner	**Convenience:** Fewer charging stops; grid independence. Lower TCO for high-mileage users.	**Upfront Cost:** Higher purchase price for the vehicle. Payback period is ~1.7–4.3 years depending on usage.	**Neutral/Positive.** Driven by convenience and autonomy rather than pure profit.
Truck Fleet Operator (ICE)	**Fuel Savings:** Solar powers auxiliary systems (A/C, fridge) instead of idling the engine. **Payback ~1 year.**	**Installation:** Retrofitting existing fleets requires initial CAPEX.	**Highly Positive.** Immediate ROI from diesel savings and CO_2 reduction.
Truck Fleet Operator (EV)	**Range Extension:** Increases effective range; reduces downtime for charging.	**ROI:** Payback period is longer (<5 years) compared to ICE trucks.	**Positive.** Essential for maximizing uptime in electric logistics.
Grid Operator	**Avoided Investment:** Reduced peak load defers need for local grid reinforcement.	**Revenue Shift:** Lower electricity transport volumes as vehicles self-generate.	**Positive.** Alleviates bottleneck pressure on the grid.
Charging Point Operator	**None:** Direct reduction in revenue due to fewer charging sessions.	**Utilization:** Lower utilization rates for public chargers may impact business models.	**Negative.** Represents a threat to traditional charging revenue models.

5. Policy Recommendations

Despite the clear benefits regarding grid stability and decarbonization, market forces alone may not drive VIPV adoption fast enough to meet EU 2030 targets. The "value network" analysis reveals a disconnect: for example, truck manufacturers are regulated on emissions, but fleet operators (who buy the fuel/electricity) reap the financial benefits of VIPV.

To bridge these gaps, the report proposes five key policy interventions:

1. Stimulate the Supply Side (Manufacturers)

- **Regulatory Framework:** Establish a clear EU-wide definition for "Solar Mobility" and integrate VIPV into the Whole Vehicle Type-Approval System.
- **VECTO Inclusion:** The VECTO tool is used to certify heavy-duty vehicle emissions. VIPV is currently not recognized in this tool. Including VIPV in VECTO (specifically the Trailer module) would allow manufacturers to count solar gains toward their CO2 reduction targets, creating an incentive for manufacturers to produce solar-equipped trailers.
- **Eco-Innovation Credits:** Expand existing eco-innovation schemes for light-duty vehicles to fully recognize the benefits of onboard solar, allowing OEMs (Original Equipment Manufacturers) to offset tailpipe emissions with solar generation credits.

2. Recognize VIPV as a Sustainable Measure

- **Renewable Energy Directive (RED III):** Explicitly classify electricity generated by vehicles as renewable energy. Currently, this energy often goes uncounted in national targets. A dedicated accounting module would validate the contribution of VIPV to the EU's renewable energy goals.

3. Incentivize the Demand Side (Owners/Users)

- **Financial Incentives:** Because the ROI for passenger cars is slow, temporary tax incentives or subsidies for VIPV-equipped vehicles can bridge the gap until production costs fall. This is crucial for early adoption. Implementing tax or subsidy benefits for solar equipped Heavy-Duty Vehicles like trailers, would immediately stimulate implementation (as done in the Netherlands at this moment).
- **Public Procurement:** Mandate or incentivize VIPV in government tenders for public transport buses and municipal fleets. This creates a stable initial market for the technology.

4. Create a Narrative and Awareness

- **Public Awareness Campaigns:** Combat scepticism by funding and disseminating fact-based pilots and user experiences. Highlight the "convenience" aspect—less charging and longer ranges —to consumer audiences.
- **Transparency:** Publish data on the CO2 abatement costs of VIPV to help the industry benchmark it against other decarbonization technologies.

Introduction

One of the key steps to successful decarbonization and a complete energy transition requires the transition away from fossil fuelled transport. The leading technology options for low- or zero - emission transport are battery electric vehicles and fuel cell vehicles. Both technologies, directly or indirectly, require an external input of electricity, thereby increasing the demand load on the electrical system grid and the need for additional electricity generation and distribution infrastructure. The challenge of effectively shifting the energy required for transportation from fossil fuels to (renewable) electricity fuels is threefold: (1) it requires a decarbonization of the grid electricity to realize the full impact for mitigating climate change; (2) it requires a major investment in infrastructure and grid capacity; and (3) new environmental problems will arise from the need for (scarce) materials and resources for batteries and fuel cells. Improvements in vehicle energy efficiency will address all these challenges by reducing the electricity demand. There are many ways to realize improved vehicle efficiency including e.g. the reduction of weight, drag reduction, mechanical or electrical losses in the drive train, and others. One option proposed is the integration of on-board solar technology (vehicle integrated photovoltaics or VIPV[1]). VIPV is not a new concept for both electric and internal combustion engine vehicles. However, the current adoption of electric vehicles supported by the governments, as well as the improvements in both performance and cost of solar PV technology, have made this a real and potentially viable option. On-board integrated photovoltaic (PV) technology is unique among these concepts as it allows for the direct creation of sustainable renewable electricity on the vehicle that can be used for any of the electrical demands of that vehicle, thus reducing the external electricity need. For a single vehicle with a specific use case, the reduced demand may be relatively small. However, when viewed at the fleet level, this impact may be significant.

The question remains, however, as to how much VIPV can contribute to reducing grid congestion and the need for infrastructure investments, required for supporting the increased uptake of electric vehicles, and to accelerating the complete decarbonization of the transportation sector, especially considering the impact of seasonal variations in solar radiation.

The SolarMoves project started in January 2023 with the main aim to investigate to what extent the expansion of VIPV would affect the electric power demand of an electrified vehicle fleet.

In the first phase of the project, a study was conducted to investigate the potential impact of VIPV on the required (charging) grid infrastructure for the future scenario of a fully electrified road transport in Europe. Simulation models were built and adapted on three different levels: 1) vehicle; 2) fleet; 3) infrastructure. The results of these investigations are described in Chapter 1, covering the overall methodology, including the definitions of vehicle types, use patterns, and how these are combined to create specific archetypes. Here, we also present the modelling in terms of impacts on energy demand and energy efficiency for both VIPV and other innovations. Subsequently, we look at the modelled impact on fleet composition and financial viability and trade-offs of different energy efficiency improvements, and we discuss the modelled impact on the grid at neighbourhood and country level.

[1] For simplicity, in this report, we do not distinguish between Vehicle Integrated PV (VIPV) and Vehicle Applied PV (VAPV). In general, PV in passenger cars will be more fully integrated into the body of the vehicle while for vans, buses, and trucks, the PV may be applied to finished external surfaces of the vehicle.

The objective of the second phase of the SolarMoves project was to gain a deeper understanding of the availability of solar resources, actual vehicle usage patterns, and the practical applicability of vehicle-level assumptions when scaled to fleet-level scenarios. To support this, a comprehensive irradiance measurement campaign was launched. This involved equipping a diverse set of vehicles—provided by industrial partners—with irradiance sensors and deploying them across Europe to capture real-world solar exposure data. The campaign included both PV-equipped and non-PV electric vehicles, enabling detailed monitoring of energy flows and providing valuable insights into their charging requirements. The findings of this phase are presented in Chapter 2.

This third and final phase of the SolarMoves project uses the results of phase 1 and 2 to perform a comprehensive analysis of costs and benefits and, based on the results of the analysis, provide policy recommendations. Details on the methodology and results of the analysis as well as the policy recommendations are given in Chapter 3.

Finally, Chapter 4 gives an overview of project management, progress and deviations and dissemination activities.

1. Methodology and Impact Assessment

The objectives of this chapter is to determine the potential of energy consumption reduction in EVs (including vehicle integrated PV) and obtain insight in the effect of improved energy efficiency on the development of the fleet composition in Europe between 2025 and 2030. Instead of performing the calculations for the whole of Europe, two locations were selected: Amsterdam, to represent Central Europe (CE) and Madrid to represent Southern Europe (SE) countries. Furthermore, within Task 1, the implications of vehicle and fleet composition evolution for the development of charging infrastructure and integration in the electricity network were assessed in these two reference years.

The objectives are to:
1. Determine the potential of energy consumption reduction options in EVs (including VIPV)
2. Obtain insight in the impact of energy consumption reduction options on the development of the fleet composition in Europe between 2025 and 2030
3. Assess the implications for the development of charging infrastructure and integration in the electricity network

The contents, logically structured along the vehicle level, fleet level and infrastructure level are outlined in Figure 2. Inputs, shown on the left-hand side, are sometimes represented by the name of the model generating them. The main results of each task are shown to the right.

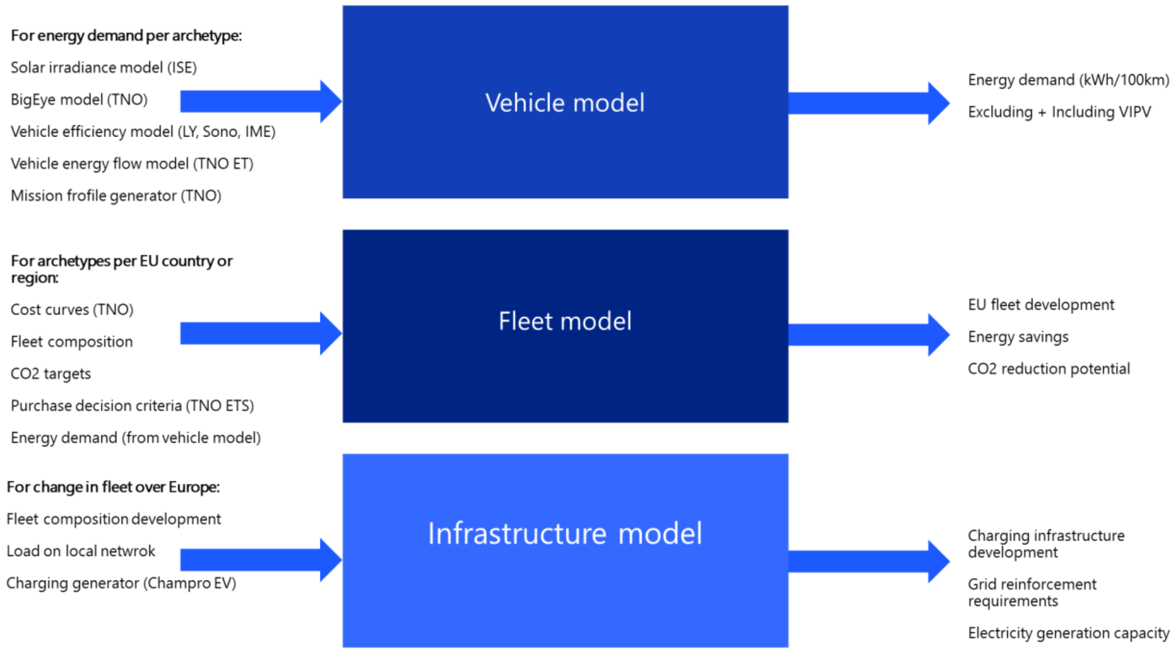


Figure 2: General model diagram with inputs and required outputs from different system level models

The results are summarised in the following key performance indicators:

A. Per archetypal vehicle (a combination of a vehicle category and a use pattern, see also paragraph 1.1.1):
   1) Improvement in external vehicle efficiency in kWh per 100 km + additional range in km in 2025 and 2030 (potential of energy consumption reduction measures + VIPV)
   2) Cost effective[2] improvement potential in internal vehicle efficiency in kWh per 100 km + additional range in km in 2025 and 2030 (potential of energy consumption reduction measures alone)
B. Potential (additional) EV fleet increase per vehicle category resulting from benefits of improved external energy efficiency (including VIPV) of vehicles
C. Potential (additional) CO_2 reduction from fleet development.
D. Unit of decreased net congestion
E. Reduced need for charging infrastructure, per vehicle category, in percent of AC chargers and percent of DC chargers.

To keep the work and results manageable, the concept of vehicle archetypes is introduced. An archetype is a combination of a vehicle class & type and a use pattern. The archetypes, which are elaborated in paragraph 1.1.1, are the basis for the vehicle model, the fleet model and the infrastructure model.

1.1 Potential for and impacts of energy efficiency gains in electric vehicles

This paragraph outlines the workflow of the Vehicle Model, which forms the foundation for assessing energy consumption and the impact of vehicle-integrated photovoltaics (VIPV) on electric vehicles. The process begins with defining vehicle specifications for each archetype, followed by generating trip profiles that reflect typical usage patterns. These profiles are then used to calculate energy consumption and final energy demand under varying PV coverage scenarios.

1.1.1. Workflow of the Vehicle Model

The workflow is depicted in Figure 3, where the following steps can be indicated:

1. Define the vehicle specifications per vehicle archetype
2. Generate the trip definitions for each archetype
3. Determine the energy consumption for each archetype
4. Determine the final energy demand per archetype for different PV coverage on the vehicles (none, sun facing surfaces only, sun facing and vertical surfaces)
5. Rerun steps 3 and 4 for efficiency improvements of all archetypes

[2] Cost effective in this case means: lower costs for the first owner of the vehicle

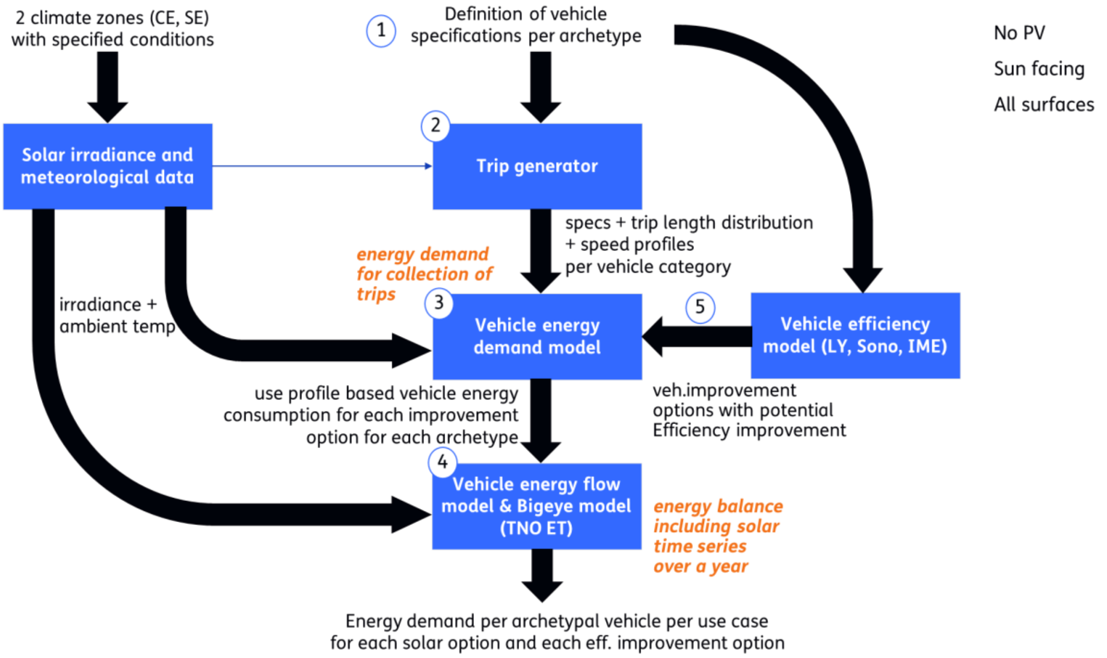


Figure 3: Workflow of the vehicle model

Because the solar irradiance and ambient temperature can have a large effect on the energy consumption of a vehicle as well as on the yield of the integrated PV, two model cities were chosen to show the extent (non-extreme situations): Amsterdam and Madrid. All analyses in Task 1 were done for both geographical locations, including the runs of the vehicle model described above.

Definition of vehicle archetypes

The potential of VIPV and other on-vehicle energy conservation, recovery or generation technologies for reduction of the grid energy consumption of an electric vehicle is highly dependent on the type of vehicle and its usage pattern. To enable a detailed assessment of the link between the vehicle and technologies, we will first define several archetypal vehicle categories, and for each a number of archetypical applications.

An archetype is a combination of a vehicle category and a use pattern. The vehicle categories are passenger car, van, bus and truck, further split out in sub-categories (e.g. small/medium/SUV for passenger cars). A use pattern is the collection of trips that a vehicle makes throughout a year, including trip weekday and time, distance, and speed profile. For each vehicle category, a few of these use patterns were chosen that together should represent the majority of uses for these vehicles. For public transport buses the use patterns were constructed as a repetitive weekly pattern of actual monitoring data of specific buses in the Netherlands. For all other use patterns a narrative was drawn up, where the use reflects a certain group of drivers (e.g. people driving to work every weekday, visiting family in the weekend etc.). The narratives were written while considering the following boundary conditions:

1. Annual mileage
2. Purpose of the vehicle
3. Urban/rural/motorway distribution of kilometres
4. Seven standard trip lengths of 5, 10, 20, 40, 100, 500 and 1000 km

For passenger cars the annual mileage was determined for every vehicle archetype using detailed data for the Dutch fleet: the mileage distribution of the Dutch fleet was cut in 3 equal-sized segments (low/medium/high) and then averaged out per segment. The resulting mileages were corrected so the 3 segments together match the annual mileage in Europe (from NL to EU = 13,329 to 11,313 km/y). The annual mileage from the vans was loosely matched with data from: Bokhorst, M. van et al, 2017[3] and Gijlswijk, R van et al, 2018[4]. The matching was done based on function of the van (catering/fresh, single-piece delivery, mail and packages, and construction). Buses were split in city buses and coaches, the data for city buses was based on average annual mileage of Dutch urban and regional buses. The annual mileage for coaches was loosely matched to data from intercity bus services in Spain from 2013-2020 and UK coach market 2018 data. The annual mileage for trucks was set at 45,000 / 80,000 / 140,000 km/y.

The distribution in urban, rural and motorway usage for each archetype was used to further distinguish the usage patterns for the vehicles. As shown in Table 1 this distribution leads to a description for each archetype and a corresponding division in local, regional and long-distance operation area. As displayed in Table 2 his resulted in 24 different vehicle archetypes, each of which is matched to a specific code.

Note that the archetypes are based on the currently predominant mobility model. The future of mobility may include different archetypes (like e.g. last mile mobility) but that is not in the scope of this project.

Table 2: Example of passenger vehicles archetypes with annual mileage and road type distribution

Vehicle type	Definition	Description	Annual mileage (km)	Urban	Semi-urban	Motorway
LP10	Light Passenger Car, occasional use	"Cars that are driven a few times a week"	3795	21%	42%	37%
LP11	Light Passenger Car, daily urban distribution	"Cars that are driven mostly in urban areas on a daily basis"	3894	70%	10%	20%
LP12	Light Passenger Car, daily peri-urban distribution	"Cars of people that live outside of the city and or use their car on a daily basis to commute to rural areas"	8099	20%	70%	10%
LP13	Light Passenger Car, highway travel	"Cars that commute most of their mileage on motorways for long-distance travel, due to business and holidays"	14479	10%	20%	70%
LP14	Light Passenger Car, car sharing		16237	26%	33%	42%

[3] Bokhorst, M. van et al, Van use in Europe and their 16237environmental impact, CE Delft, September 2017
[4] Gijlswijk, R. van et al, Elektrische bestelauto's in Nederland – marktontwikkelingen 2017-2025, TNO, CE Delft and Connekt, August 2018

Table 3: List of selected archetypal vehicles

Code	Cat.	Vehicle class and type	Use pattern
LP10	LD	Small passenger car	'occasional use'
LP11	LD	Small passenger car	‘daily urban commute’
LP12	LD	Small passenger car	‘daily peri urban commute’
LP13	LD	Small passenger car	‘long-distance highway travel’
LP14	LD	Small passenger car	‘car sharing’
LP21	LD	Medium sized passenger car	‘daily urban commute’
LP22	LD	Medium sized passenger car	‘daily peri urban commute’
LP23	LD	Medium sized passenger car	‘long-distance highway travel’
LP31	LD	SUV	‘daily urban commute’
LP32	LD	SUV	‘daily peri urban commute’
LP33	LD	SUV	‘long-distance highway travel’
LV11	LD	Small van	‘Local distribution’
LV12	LD	Small van	‘Regional distribution’
LV21	LD	Large van	‘Local distribution’
LV22	LD	Large van	‘Regional distribution’
HB11	HD	Low-floor bus	‘Urban public transport service’
HB12	HD	Low-floor bus	‘Peri urban public transport service’
HB22	HD	High-floor coach	‘Regional public transport’
HB23	HD	High-floor coach	‘Long-distance highway travel’
HT11	HD	Rigid truck	‘Urban distribution’
HT12	HD	Rigid truck	‘Regional distribution’
HT22	HD	Tractor-trailer	‘Regional distribution’
HT23	HD	Tractor-trailer	‘Long-haul freight transport’

The first column is a code to refer to the archetype: L for light duty and H for heavy duty, P, V, B, T for the vehicle categories passenger car, van, bus and truck, the first number as a counter for the variant, and the second number for typical use pattern, strongly associated with the normal operation area (1 for local, 2 for regional and 3 for long-distance).

For defining the vehicle archetypes and their characteristics, several sources, methods and assumptions have been used.

Characteristics of each archetypal vehicle

Each archetype has physical properties such as mass, as well as usage properties, such as annual mileage and shares of different road types. The properties of each archetype are chosen in such a way that they represent a segment of the electric vehicle fleet.

The characteristics were determined in a three-step approach:

1) Create the *types* for each vehicle class; this leads to distinguishing properties for each vehicle type in
2) The first column is a code to refer to the archetype: L for light duty and H for heavy duty, P, V, B, T for the vehicle categories passenger car, van, bus and truck, the first number as a counter for the variant, and the second number for typical use pattern, strongly associated with the normal operation area (1 for local, 2 for regional and 3 for long-distance)**.**
3) (e.g. small van - large van)

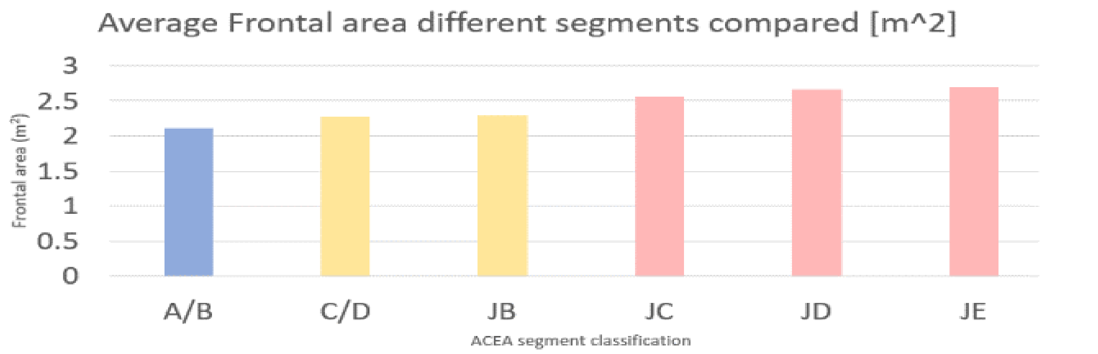
4) Derive properties for each of the vehicle types based on the presently most common vehicle brands/models/variants in the fleet
5) Derive typical use pattern characteristics to distinguish archetypes within each vehicle class & type

Step 1: from vehicle class to vehicle type

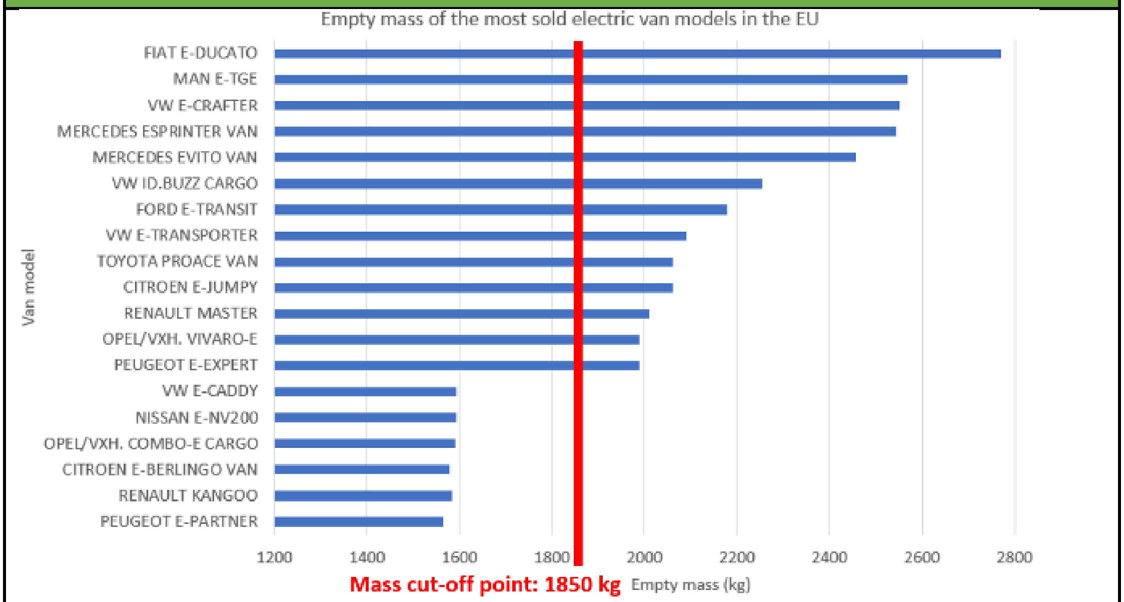
The approach to step 1 is explained in Table 4.

Table 4: From vehicle class to vehicle type

<table>
<tr><td>Passenger cars</td></tr>
<tr><td>



The definition of small, medium and SUV passenger cars is almost the same as the ACEA classification[5], that the European Commission follows. Except that small SUV's (JB) is added to the medium category, as it is more comparable to that category in terms of characteristics.</td></tr>
<tr><td>Vans</td></tr>
<tr><td>



The two categories, small and large vans, are distinguished by reference mass. In the European Directive 2007/46/EC, vans (N1) consist of three categories (I, II and III). The mass cut-off point is set at the half point of the reference mass range of category II times a multiplication factor due to the larger mass of electric vans compared to diesel vans.</td></tr>
</table>

[5] EU classification of vehicle types, https://alternative-fuels-observatory.ec.europa.eu/general-information/vehicle-types (retrieved in May 2023)

Trucks
At the moment when the project was prepared, there weren't many electric trucks deployed yet. The characteristics are based on the electric models of the brands Volvo, Mercedes, DAF and Renault. Together, these companies represent 60% of the conventional market.
Buses
The characteristics of the low-floor bus are based on the average characteristics of the top 8 most registered electric buses in the Netherlands (83%). Since there are no electric coaches deployed yet in the EU, the characteristics of the coach are the same as for the low-floor bus.

Dimensions, weight, battery size and electric motor power are all obtained by taking the average of a selection of models for each vehicle type. This is described hereafter.

Step 2: characteristics of each archetype

We obtained most vehicle characteristics by taking the average of the properties of the top-5 or top-10 most sold EVs in the EU per category for the years 2020, 2021 and 2022. The sales data was obtained from EAFO (European Alternative Fuels Observatory) for light duty vehicles, and extrapolated from the Dutch fleet data, obtained from the Dutch type approval authority, for buses and trucks. As an example, the top-10 is shown for passenger cars in Table 5.

Table 5: Input to archetype characteristics: top-10 most sold battery- electric passenger cars in EU27 in 2020, 2021 and 2022 combined

Small	Medium	SUV
RENAULT ZOE	TESLA MODEL 3	TESLA MODEL Y
FIAT 500E	VW ID.3	VW ID.4
PEUGEOT E-208	HYUNDAI KONA	SKODA ENYAQ
DACIA SPRING	NISSAN LEAF	KIA E-NIRO
VW E-UP!	PEUGEOT E-2008	AUDI E-TRON QUATTRO
SMART FORTWO	POLESTAR 2	AUDI Q4 E-TRON
MINI COOPER SE	OPEL/VXH. MOKKA-E	HYUNDAI IONIQ 5
RENAULT TWINGO	RENAULT MEGANE	VOLVO XC40
OPEL/VXH. CORSA-E	CUPRA EL-BORN	FORD MUSTANG MACH-E GT
BMW I3	VW E-GOLF	MERCEDES EQA

Each vehicle has an equal weighting factor, to avoid tuning the results to a specific vehicle model that dominates the sales. Properties for the top-10 include: battery capacity, dimensions, motor power, mass. These properties were derived from the database of the Dutch fleet, as provided by the type approval authority[6]. Frontal area was estimated from the height and width and a vehicle category-specific multiplication factor. Maximum AC charging rates were selected to be 3.7 kW for LP1x archetypes and 11 kW for all other light duty archetypes. See also the specifications in EV-database[7]. Charging losses are described in the next paragraph.

The top-5's and top-10's per vehicle class and their properties are listed in Appendix A.

[6] opendata.rdw.nl, 'basisregistratie voertuigen'
[7] ev-database.org

Step 3: Use pattern

The use pattern for each archetype is modelled as a set of trips throughout the year, following a narrative that describes a common use pattern. The resulting annual use for each archetype complies to pre-set boundary conditions: annual mileage, share of urban/rural/motorway driving and trip length distribution. This approach is elaborated in paragraph 1.1.2.

Charging losses and other non-use related consumption

To determine the AC charging losses, various documents were studied. In the report by van Gijlswijk et al.[8] from 2021 an overview of charging and battery cycle losses is given for various electric vehicles. The overview shows a charging loss between 10 and 21%. Reick et al. [9] come to roughly similar numbers[10] between 12.8 and 20.4%. The Dutch National Automotive Association (ANWB) report an average number of 15%.[11] The German national automotive association reports measured numbers between 12.7 and 24.2%.[12] Based on the reported numbers an average AC charging loss of 15% was used. This number is kept constant for the period under study: 2023-2030.

For DC, it is more difficult to find information on the charging losses. One paper found charging losses of around 10% (at 25 ^{0}C) [13]. This number was therefore used for the DC charging loss. Note that it is in the interest of the charger operator to have equipment with small losses, because the vehicle user pays per delivered kWh, not per kWh taken up from the grid.
For losses from PV charging a value the figure of 4.5% was used, as supplied by partners (Lightyear).
Self-discharge of the battery is not taken into account but is considered a minor factor for lithium-ion batteries.
Standby consumption of electronic control and communication systems on board of an electric vehicle is not taken into account, but might be significant for light duty vehicles. They cause gradual battery discharge while the vehicle is parked unplugged. Limited data is available at the moment.

Battery temperature management and/or interior preheating while plugged in is considered part of the total energy consumption of the vehicle.

[8] Real-world fuel consumption and electricity consumption of passenger cars and light commercial vehicles – 2021; Real-world fuel consumption and electricity consumption of passenger cars and light commercial vehicles - 2021 | Rapport | Rijksoverheid.nl
[9] Reick, B.; Konzept, A.; Kaufmann, A.; Stetter, R.; Engelmann, D. Influence of Charging Losses on Energy Consumption and CO2 Emissions of Battery-Electric Vehicles. Vehicles 2021, 3, 736-748. https://doi.org/10.3390/vehicles3040043
[10] Reick, B.; Konzept, A.; Kaufmann, A.; Stetter, R.; Engelmann, D. Influence of Charging Losses on Energy Consumption and CO2 Emissions of Battery-Electric Vehicles. Vehicles 2021, 3, 736-748. https://doi.org/10.3390/vehicles3040043
[11] https://www.anwb.nl/auto/elektrisch-rijden/opladen/laadverlies-thuisladen-elektrische-auto
[12] https://www.adac.de/rund-ums-fahrzeug/elektromobilitaet/laden/ladeverluste-elektroauto-studie/
[13] Energies | Free Full-Text | Evaluation of Fast Charging Efficiency under Extreme Temperatures (mdpi.com)

Charging

Boundaries are set to minimum and maximum battery state of charge in normal use, see Table 6. The table also shows the efficiency of the vehicle integrated PV.

Table 6: Battery charging parameters

parameter	Percentage of user available battery capacity	comments
Battery minimum SoC	10%	
Maximum SoC, AC charging	90%	Unless strategy 4 then limited by space allowance setting for PV. When using the charging strategy for optimising PV, the maximum SoC is lower, see paragraph 1.1.6
Maximum SoC DC charging	75%,	75% limit, then charging rate drops to 40% of fast charge rate
Maximum SoC PV charging	100%	As PV charging is a much lower rate, essentially a trickle charge, the maximum is set to 100% if only charging from PV

1.1.2. Trip generator

As depicted in Figure 3, after determining the vehicle-related input parameters, the trips per vehicle archetype and use case are calculated. This is done by first determining the use patterns.

The use pattern is characterised by:
- annual mileage
- road types and trip lengths
- trip pattern (depends on the vehicle type and mission)

Annual Mileage

The annual mileage was determined for every vehicle archetype using detailed data for the Dutch fleet (ODIN data, 2019), and correcting the outcome to ensure the average mileage per category (passenger cars, vans, buses, coaches, trucks) matches the European average mileage.

First, out of the Dutch passenger car fleet three groups were created: small passenger cars, medium sized passenger cars, and SUVs. Each group was split in three equally sized parts, based on annual mileage from small to large. Extremes were disregarded, such as unused vehicles (<1460 km/y) and very high mileages (>55,115 km/y). Of the three equal parts, the median mileage was taken for the archetypes LPx1, LPx2, and LPx3.

The average annual mileage of passenger cars in the Netherlands is 13,329 km, while in Europe this is 11,313 km/y (Odyssee, 2019). Therefore, all calculated mileages were multiplied by a factor of 0.85. Annual average mileages of vans were loosely matched with data[14,15] by function: catering/fresh for LV11, single-piece delivery for LV12, mail and packages for LV21, and construction for LV22.

[14] Bokhorst, M. van et al, Van use in Europe and their environmental impact, CE Delft, September 2017
[15] Gijlswijk, R. van et al, Elektrische bestelauto's in Nederland – marktontwikkelingen 2017-2025, TNO, CE Delft and Connekt, August 2018

The annual mileage for trucks is brought in line with the split commonly used in VECTO: below 80,000 km/year a vehicle is considered a regional delivery truck, above this limit a vehicle is used for long-haul (SR9).

For buses the average mileage was derived from real-world (emissions) monitoring of diesel buses in Amsterdam (urban) and ‘s-Hertogenbosch (regional bus service). Because the Amsterdam service would imply an extremely high annual mileage compared to the average, the last nightly hours of service were cut off to make it more representative. Also, for both the urban and regional bus data, some charging stops were introduced where needed.

The mileages used for the assessment are close, but not exactly matching the values from statistics, because they are constructed by adding up a large number of standardised trips. The values used for the assessment are shown in Figure 4.

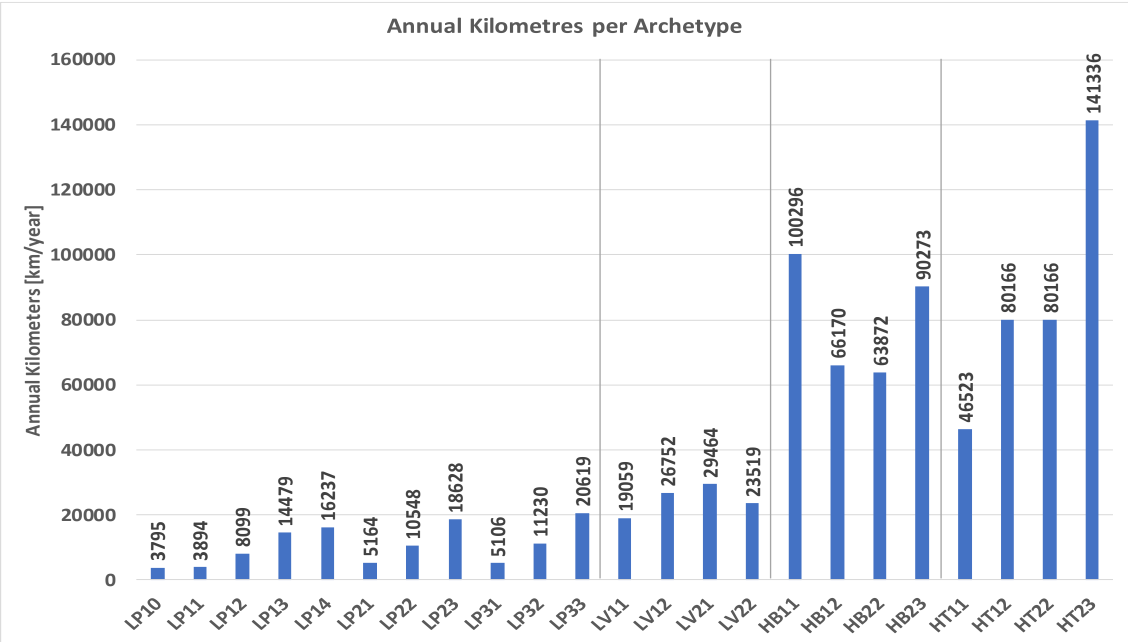


Figure 4: Annual kilometres per vehicle archetype

Road types and trip length

As mentioned in Appendix A the ratio of urban, rural and highway driving is a boundary condition in the assessment as well. For each archetype a ratio was assumed, based on literature. The assumed ratios can be found in Appendix B.

The annual use of each archetype, consisting of a collection of trips, has to comply to the annual mileage, urban/rural/motorway share and to a trip length distribution dependent on the use narrative.

To keep the calculations manageable, a standard set of 7 trips was defined. A trip consists of a route and a desired speed profile. These standard trips are used for all archetypes, in different ratios and with a different schedule. Naturally, the actual speed profile and energy consumption will be different for the different archetypes, dependent on the vehicle characteristics. The trips have an approximate distance of 5, 10, 20, 40, 100, 500 and 1000 km, and have a varying urban/rural/motorway share. The trips were actually planned from a point A to a point B on the map. The speed (limit) profile is derived with the Open-Source Routing Machine (OSRM, https://project-osrm.org). The annual usage of each archetype is composed of a combination of the seven trip types: the trip pattern.

Trip pattern

For each archetype except HB11 and HB12, a full-year trip planning was made, consisting of a combination of the abovementioned seven standard trips. The trip pattern follows a narrative describing a common use type. For instance, LP12 is described as "cars of people that live outside the city and use their car on a daily basis to commute to rural areas". The trips include a daily commute to work, as well as some weekly trips to run errands, family visits in the weekend and a holiday trip in August. Each trip has a start time (e.g. 9:00 and 17:00 for commuting).

The frequency of the standard trips is chosen in such a way that adding up all trips results in the urban/rural/motorway driving shares set as a boundary condition.

For public transport buses HB11 and HB12, the timing and speed profile of an actual week's service in respectively Amsterdam and 's Hertogenbosch was taken and adapted to allow for charging where needed.

Appendix B contains tables that show the trip pattern for each archetype.

1.1.3. Vehicle Energy Demand Model

Route and Mission profile

For the creation of a mission profile for each of the seven standard trips, a similar methodology has been used as in a previous European project – AEROFLEX[16], where the models and the methods have been described in detail. The steps are shown in the schematic in Figure 5 where the vehicle drives a trip from an origin to a destination.

Each step is described below:

- Based on the origin and destination (and any intermediate stops) of the trip, a route is planned in OpenStreetMap. This results in a schematic representation of the route in terms of distance, elevation (based on SRTM[17] and filtered to prevent unrealistic slopes) and speed-limit. The speed-limit (as obtained from OpenStreetMap) is corrected to match the expected speed on the road as obtained from TomTom navigation API. This gives more insight into the real-driving speed on the roads. To make sure the traffic is taken into account, the TomTom navigation gives insight into average speeds of traffic on small segments of the road along the route. This, in principle, should take into account the traffic lights and crossings along the route (if any). The target speed-limit is then the minimum of the speed-limit of the road and the traffic speed obtained from TomTom navigation.

[16] Eijk, E. van, Aerodynamic and Flexible Trucks for Next Generation of Long Distance Road Transport, Horizon 2020 AEROFLEX deliverable 6.2: Assessment framework, November 2019.
[17] https://www2.jpl.nasa.gov/srtm/

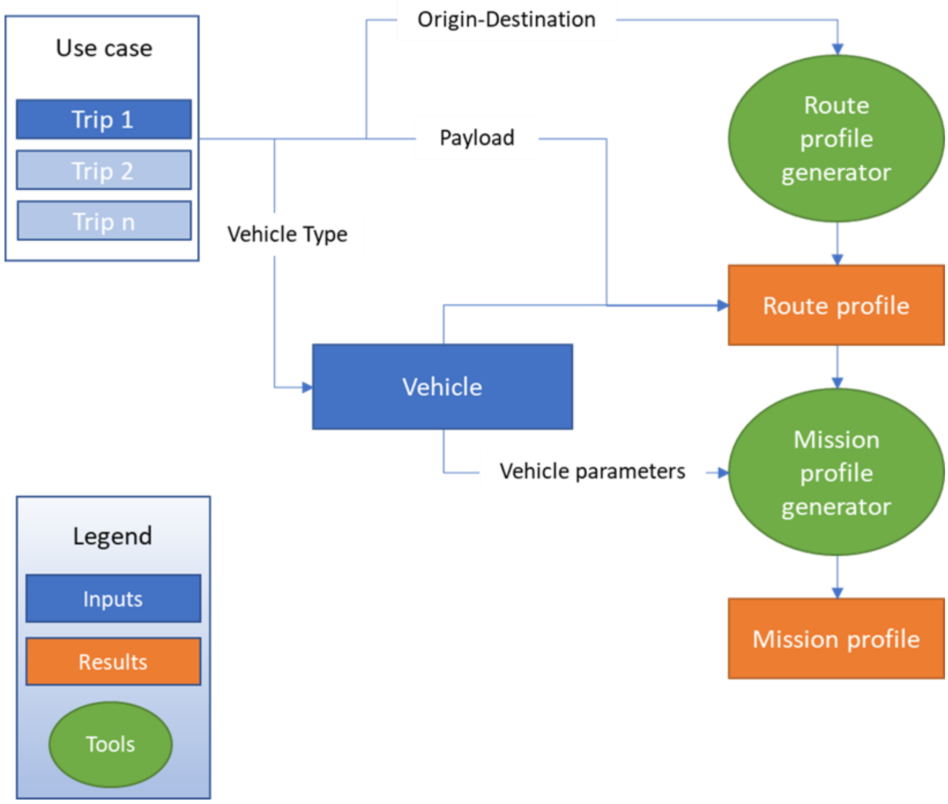


Figure 5: A schematic overview of the route and mission profile generator, the inputs needed, thereby showing a single trip formation

- With the speed-limit (corrected with the TomTom navigation API) as the target speed, the vehicle with a certain payload is simulated over the route profile to get a mission profile – a time-based speed and slope profile. This is done assuming a maximum speed and is based on a very simple driver model; considering a constant deceleration if the vehicle speed is more than the speed limit of the road and a constant acceleration if the vehicle speed is less than the speed limit of the road. The values of the maximum velocity and acceleration and deceleration are shown in Table 7.

Table 7: Values of maximum velocity, acceleration and deceleration chosen for each of the vehicle types

Vehicle type	Maximum velocity [km/h]	Constant Acceleration [m/s²]	Constant deceleration [m/s²]
Passenger Car	100	1.5	2
Van	100	1.5	2
City bus	85	1	1.5
Coach	100	1	1.5
Rigid Truck	85	0.5	1
Tractor-trailer	85	0.5	1

MEO model

The energy consumption of the vehicle driving a particular route is calculated using a simulation model called MEO (Multi-level Energy Optimisation), previously developed at TNO. The electric vehicle model was improved for SolarMoves.

The mission profile created is fed as input into the MEO model which calculates the total energy consumption for the trip on a 1Hz basis. The schematic of the MEO model is represented in Figure 6.

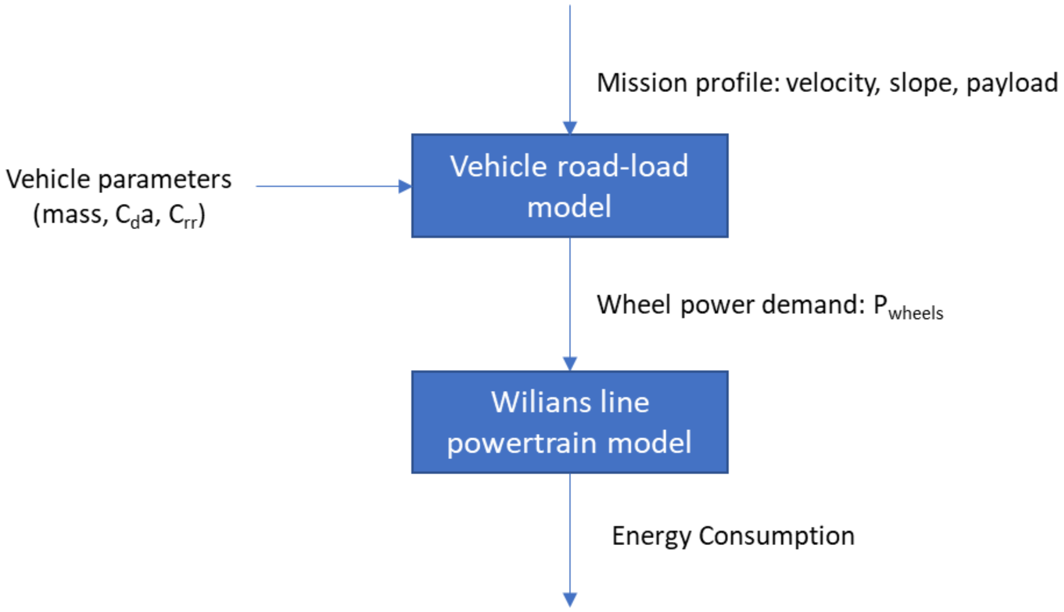


Figure 6: Schematic of the MEO model

The MEO model is a physics-based model that calculates the power required at the wheel from the vehicle characteristics and a mission profile. The power at the wheel is calculated using the following equation;

$$P\ wheel\ [kW] = P\ Intertia\ [kW] + P\ Rolling\ [kW] + P\ Gradient\ [kW] + P\ drag\ [kW]$$

A constant efficiency of the battery and charger are assumed to calculate the total energy needed from the battery as shown in Table 8. These values are needed for e.g. regenerative braking and are (when combined) in line with the values for grid charging.

Table 8. Efficiencies of the battery, charger and generator as chosen in the MEO model

Variable [unit]	Value
Efficiency of the battery charging [%]	95
Efficiency of the battery discharging [%]	95
Efficiency of the charger [%]	90
Efficiency of the generator [%]	90

HVAC model

The power required for heating, ventilation and air-conditioning for each of the vehicle archetypes was calculated separately as it depends on the outside temperature. The 1Hz output from the MEO model was converted to a 10-minute interval output to better capture the effects of temperature and to be able to incorporate the meteorological data from both Amsterdam and Madrid into the output. This was also a necessary step to incorporate the results from the model into the Energy Flow Model (EFM) model for solar yield.

For the calculation of the energy consumption of conditioning the cabin, dependent on the ambient temperature, formulas were derived from literature study and work done earlier at TNO. The formulas and sources are reported in appendix C.

Charging stops

For trips longer than 100 km, fast charging during the trip may be required. To determine the timing and duration of the required stops, the trip profile is divided in segments. The length of these segments is determined by the usable battery capacity, the average motorway energy consumption of the vehicle, a charging rate of 1.3C and a safety margin to allow higher energy consumption resulting from for instance extreme temperatures. It is assumed that the first run starts with 90% state of charge of the battery. Successive fast charging sessions are assumed to take 30 minutes and charge from 10% to 75% state of charge[18]. The last session can be shorter, dependent on the remaining distance. These numbers are representative for passenger cars, but assuming the charging speed scales with the battery capacity, these factors are applied to all vehicle archetypes.

Location of the vehicle

In the next step, the Vehicle Energy Flow Model determines when the vehicles are charged. If the location of the vehicle is largely known, it can be determined what type of charging (AC/DC) may be used, and at which rate. To this end, the driving profiles are processed on a day-to-day basis. Passenger cars, vans, low-floor buses and local and regional trucks are assumed to be at base (home, company parking, bus depot) at night. For passenger cars, dependent on the number and purpose of trips, it returns to base in between trips or it remains parked on the street between trips. The other vehicle types always remain on the street during the day, and return to base after the last trip of the day. Long-distance coaches and trucks are assumed to never return to base. During long trips, fast charging close to the motorway is assumed.

1.1.4. Trip definitions

Road types and trip length

We determine and combine the following road and trip types that can be taken within the simulations:

- Urban areas: 5 and 10 km trips
- Rural areas: 20 and 40 km trips
- Motorways: 100, 500 and 1000 km trips

Trip specification

Each trip type specification will cover a full year of operation in 10-min intervals. The total number of trip types is distributed over the year and together should form the average annual mileage for the vehicle archetype with the specific use pattern.

[18] Average for 159 electric vehicle tests, see https://tbtp-ev.github.io/tbtp-results-range.html and https://drive.google.com/drive/folders/1HOwktdiZmm40atGPwymzrxErMi1ZrKPP

For most vehicle archetypes there are 2 holiday weeks taken into account where no commuting trips are taken. Instead long-distance travels (holidays) are taken into account in these weeks. These holiday weeks are highlighted in the trip distribution over the year.

The trip specification is rather detailed, as for the solar electric vehicle the energy generated from the PV panels strongly depends on the time at which the trip is taking place and the day in the year. In this way, hourly and seasonal effect are taken into account.

Trip definitions for each archetype

Table 9 gives an overview of the trip definition for a small passenger car. A detailed description of all the trip definitions for all archetype vehicles can be found in Appendix B.

Table 9: Description of passenger vehicle archetypes, including annual mileage and distribution over road types

Vehicle type	Vehicle class and type	Use pattern	Description	Annual mileage (km)	Urban	Rural	Motor-way
LP10	Small passenger car	Occasional use	Cars that are driven a few times a week	3795	21%	42%	37%
LP11	Small passenger car	Daily urban commute	Cars that are driven mostly in urban areas on a daily basis	3894	70%	10%	20%
LP12	Small passenger car	Daily periurban commute	Cars of people that live outside the city and/or use their car on a daily basis to commute to rural areas	8099	20%	70%	10%
LP13	Small passenger car	Long-distance highway travel	Cars that commute most of their mileage on motorways for long-distance travel, due to business and holidays	14479	10%	20%	70%
LP14	Small passenger car	Car sharing		16237	26%	33%	42%

Figure 7 shows an example of one archetype.

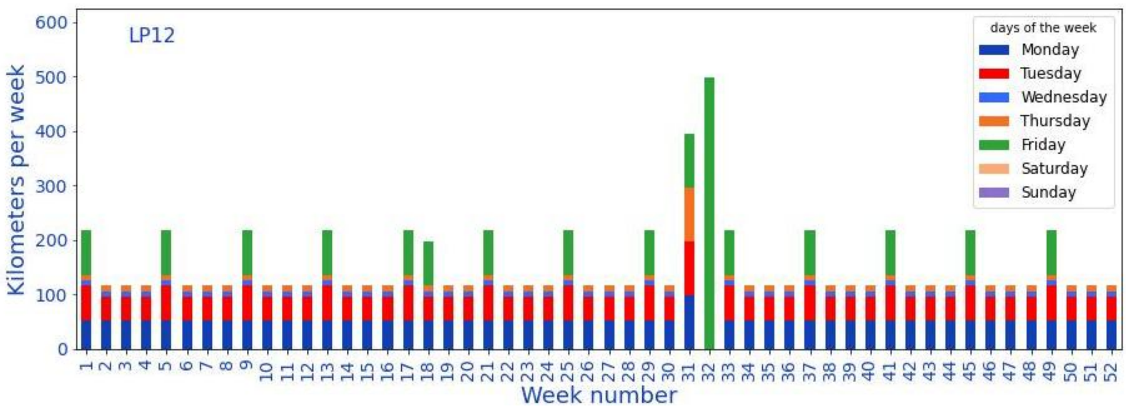


Figure 7: Example driving profile over the year for LP12. Showing weekly kilometres driven, with the different colours representing the days of the week. On the x-axis are the weeks of the year.

These trip definitions are subsequently fed into the energy flow model.

1.1.5. Vehicle Energy Flow Model & BigEye

Solar electric vehicle types

Each vehicle archetype is represented by 2 solar electric vehicle variants, resulting in a total of 3 variants per vehicle archetype:

1. without PV solar
2. sun facing PV (more or less horizontal vehicle surfaces)
3. full solar PV coverage (both horizontal and vertical vehicle surfaces)

To assess the impact of VIPV these trips are being generated for the environmental conditions in both the Netherlands (Central Europe) and Spain (Southern Europe).

To assess the impact of VIPV on the energy consumption from the grid, the input from the trip definition end energy demand model is fed into the Energy Flow Model. In the model a PV efficiency of 21% is used.

1.1.6. Vehicle Energy Flow Model

The Energy Flow Model (EFM) was developed by TNO as a detailed energy balance model of vehicle energy use and on-board PV yield in finite time steps over a full year. The time steps can be varied to match the available input data such as irradiance or vehicle location. The model calculates the kWh required for driving ($E_{req.}$) and balances this against the energy supplied by the PV system for each time step (E_{PV}), and the resulting change in energy stored the battery ($\Delta E_{bat.}$), according to:

$$E_{PV}\,(t) - E_{req.}(t) = \Delta E_{bat}(t)$$

The energy in the battery at any time is defined by the state-of-charge (B_{SOC}) of the battery multiplied by the useable capacity of the battery, C_{bat}. Therefore,

$$\Delta E_{bat}(t) = \Delta B_{SOC}(t) C_{bat}$$

Based on the battery state-of-charge (SoC) during any time step, an algorithm for the charging strategy is used to decide whether to charge from the grid.

The EFM model takes into account the meteorological conditions (Global Horizontal Irradiance, Diffuse Horizontal Irradiance, ambient temperature and windspeed) at the vehicle location, using 10-minute interval meteorological data from Meteonorm. An overview of the VIPV-related vehicle specifications used in the model is given in Table 10. Note that the (highway) fast charge rates correspond to charging from 10% to 75% in 30 minutes. The rates are capped to 389 kW, corresponding to 350 kW after losses.

Two Base or Home charge rates are used for small passenger cars and for medium passenger cars. This is to account for people who can plug in at home, or have to use street charging at home.

Table 10: VIPV-related vehicle specifications for use in EFM

		Available PV area [m²]		Charge rates [kW]		
Vehicle type	Usable batt. cap. [kWh]	Horizontal sun facing surfaces	Vertical sides (per side)	Base (home)	Street / or work	Highway
Small passenger car	34.4	2	0.7	3.6 or 11	11	49.7
Medium passenger car	59.0	2.64	0.95	3.6 or 11	11	79.4
SUV	72.0	4.2	1.2	11	11	103.8
Small van	40.9	4.26	1.23	11	11	59.1
Large van	67.4	6	1.75	11	11	97.3
Low-floor bus	290	8	3.54	50	50	389
High-floor coach	290	8	3.54	50	50	389
Rigid truck	266	14	16	50	50	389
Tractor-trailer	397	25	28	50	50	389

Charging strategies

The EFM has several charging strategies. For each simulation separate calculations were made for have applied the following three different strategies:

A) Conservative look ahead: Look ahead to energy required for next day or next drive – if charging required, then charge to 90%.
B) Optimised for PV: same as conservative look ahead but instead of charging to 90%, space is left (20%-45%) in the battery to accept PV energy.
C) Plugged in: Plugged in all the time with a set parking limit. If parked for x hours then plug in. x is 1 or 2 hours

1.1.7. Energy yield calculations

For calculations of the PV energy yield, the TNO built BigEye model[19] is used. BIGEYE is an advanced PV modelling package developed by TNO in order to address shortcomings in commercial PV yield calculators for advanced PV technology like bifacial modules, modules under dynamic conditions, and 3D shaped modules. BIGEYE is called in the EFM model to calculate the energy yield from the PV component in any time period taking into account system electronics and PV orientation.

This model calculates the energy yield of PV systems at a given location. Minimal inputs are the module specifications, bearing angle, and a set of time-dependent meteorological data containing at least the Global Horizontal Irradiance (GHI) and ambient temperature. Diffuse horizontal irradiance (DHI) can be supplied or calculated. If wind speed data is provided, it can be used in the thermal model, to determine the temperature dependent PV yield. Parts of this model were published before.[20] For vehicles, a shading function is added. This will be explained in more detail in the next paragraph.

[19] Bifacial solar panels | TNO
[20] A.R. Burgers, BIGEYE - simulation under shadow conditions, presented at the 6th Workshop on Bifacial PV, Amsterdam (Sep. 2019)

Irradiance function

There is not much information on the shading on cars induced by buildings and trees along roads. The thesis of Cobbenhagen[21] showed some measurement results, with a sinusoidal seasonal distribution of the daily average irradiance factor. On a yearly basis, this results in a shading loss of 35%. However, this does not take into account differences between different types of routes, like urban, semi-urban and highway routes. For this the work of Araki et al.[22] was used. They calculated a reduction in global horizontal irradiance of 3% in open areas, 21% residential regions and 48% in built areas. These correspond roughly to the Motorway, Semi-Urban and Urban areas as used of the SolarMoves project. The numbers are based on the latitude of Amsterdam. For the SolarMoves project we took intermediate numbers incorporate the fact that in the Netherlands there are not that completely open areas and the Urban routes are often a mix between real city centre and more low-rise residential parts. The seasonal irradiance factors are shown in

Figure 8 and result in an average annual shading loss of:
- Urban: 35%
- Semi-urban: 24%
- Motorway: 15%

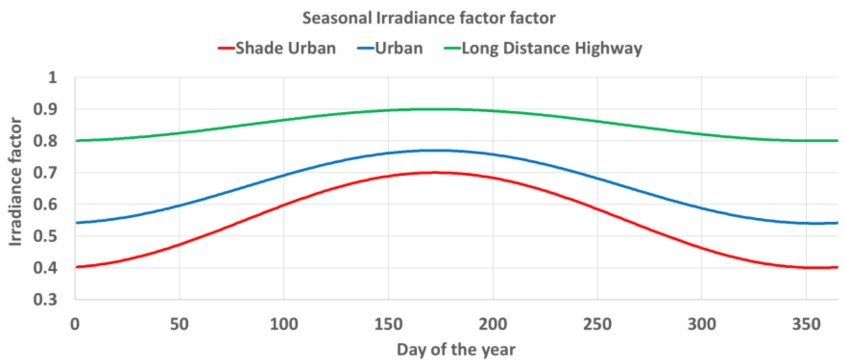


Figure 8: Seasonal irradiance factor for different road types. The irradiance factor is the fraction of the solar light received by the VIPV during a trip on a certain road type in comparison to the amount of solar light received on a trip without any shading losses

This section quantified vehicle-level energy efficiency gains from VIPV across a wide range of vehicle archetypes and use patterns, using a consistent modelling framework that integrates driving behaviour, charging strategies, and solar availability. The next section builds on these results by analysing how these efficiency gains translate to changes in EU fleet composition and aggregate energy demand.

1.2 Energy efficiency impacts on EU fleet composition

In the next step we examine how VIPV can reduce energy consumption at the charger, describing the changes to key parameters including EV ranges, charging times, and costs. The effect of PV is put in perspective by adding a package of other possible energy consumption reduction options to

[21] Performance analysis of solar cars for everyday use — Eindhoven University of Technology research portal (tue.nl)

[22] Araki, K.; Ota, Y.; Nagaoka, A.; Nishioka, K. 3D Solar Irradiance Model for Non-Uniform Shading Environments Using Shading (Aperture) Matrix Enhanced by Local Coordinate System. Energies 2023, 16, 4414.

the vehicles in the analysis. This information is subsequently used in a fleet level assessment to estimate how many of these archetypal vehicles and with which efficiency options could be considered operational in Europe in two reference years 2025 and 2030 and how these options might affect the share of battery electric vehicles (BEVs) in the fleet. This fleet level assessment uses costs of ownership information including the key parameters mentioned above, as well as statistical information about the use patterns of vehicles, and estimates the (potential) effectiveness of the energy consumption reduction options on a European fleet level, taking into consideration local conditions (e.g., solar irradiation, speed limits, share of urban/rural/highway driving). Practical usability is considered a boundary condition for the actual uptake / fleet development.

1.2.1. Energy consumption reduction options

For each of the four vehicle categories, a shortlist of ~10 energy consumption reduction options were compiled. The options on the list are already feasible from a technical viewpoint. Whether these are economically attractive to the first user of the vehicle was assessed by comparing the implementation costs with the avoided electricity costs, calculated over five years. The effect and price of each option was established in a workshop among the project partners. The electricity savings were calculated by changing the vehicle properties (once for each option) and re-running the vehicle energy demand model for each archetype. This was done because the effectiveness of each option is partially determined by the driving profile. The options, which were deemed viable in 2025 and in 2030, were combined in a package for each archetype. These adjusted archetypes formed the baseline 2025 and 2030 vehicles for the total cost of ownership model.

1.2.2. Total cost of ownership

The total cost of ownership (TCO) consists of all costs during the use period of 5 years. It is the summation of the Capital Expenditures (CAPEX) and Operating Expenditures (OPEX). CAPEX is calculated by subtracting the residual value from the purchase cost. Discounting is applied to costs made after the purchase moment, using 8% for companies and 2.25% for private owners. The OPEX consists of energy costs, maintenance costs, taxes and insurance costs. The TCO is calculated for 8 different configurations of all vehicle archetypes over the associated timeframes:

- 2023
    - Baseline 2023
    - Baseline 2023 + PV on sun facing areas
- 2025
    - cost-effective energy reduction options 2025
    - cost-effective energy reduction options 2025 + PV on sun facing areas
- 2030
    - cost-effective energy reduction options 2030
    - cost-effective energy reduction options 2030 + PV on sun facing areas
- Ultimate
    - all considered energy reduction options
    - all considered energy reduction options + PV on sun facing areas

For the ‘ultimate’ scenario, the full list of energy reduction options were assumed to be implemented, regardless if they are deemed economically viable. For mutually exclusive options, the best/most effective option was taken.

A detailed description of the grid energy reduction options for each configuration is given in paragraph 2.2.1. Table 11 gives an overview of the TCO parameters and assumptions for the different archetypes and Table 12 and Table 13 provide an overview of present and future costs of VIPV for passenger cars, trucks and buses.

Table 11: TCO parameters and assumptions

<table>
<tr><th></th><th>Light Duty (LPxx and LVxx)</th><th>Heavy Duty (HTxx and HBxx)</th></tr>
<tr><td>Perspective</td><td colspan="2">User perspective over use period of 5 years</td></tr>
<tr><td>Purchase costs</td><td>Catalogue prices of the Netherlands.
Price development based on an EV cost development study by ICCT, 2022 [23].</td><td>Trucks prices and price development based on methodology in T&E study[24]. Electric bus price based on the known price in 2019 [25] applying battery price development from T&E study[24].</td></tr>
<tr><td>Residual value</td><td>Annual and km-based depreciation factors obtained from regression analysis of 649 EV's in the Netherlands in 2018.</td><td>Annual depreciation of 7.5% and km-based depreciation (residual value = 0 after $1.5 \cdot 10^6$ km) [24].</td></tr>
<tr><td>Energy costs</td><td colspan="2">Obtained from multiplying the external efficiency by the total mileage and weighed electricity price. The weighed electricity price is calculated by weighing the share of home/street/fast charging per archetype against the home/street/fast electricity prices. The external efficiency of each archetype changes per configuration. Charging losses are included. Electricity prices were derived by weighting charging tariffs throughout Europe with the present share of each country in the European EV fleet [26] The electricity prices are kept constant over 2023 – 2035 and include taxes.
<table>
<tr><th>Electricity prices (€/kWh):</th><th>Home / depot</th><th>Street</th><th>Fast</th></tr>
<tr><td>Light Duty</td><td>0.276</td><td>0.489</td><td>0.576</td></tr>
<tr><td>Heavy Duty</td><td>0.197</td><td>0.197</td><td>0.576</td></tr>
</table></td></tr>
<tr><td>Maintenance costs</td><td>€0.059 / km for both [27]</td><td>HTxx: €0.132 / km [24]
HBxx: €0.15 / km [27]</td></tr>
<tr><td>Insurance costs</td><td>Varies based on purchase price [28]
On average €800 / year</td><td>HT1x: €3200/year, HT2x: €2000/year [27]
HBxx: €2000/year [27]</td></tr>
<tr><td>Taxes</td><td>EV taxes near zero for most EU countries. Average ownership tax €40 per year. [29]</td><td>Road tolling per km and per year is included for HTxx [24], no ownership taxes included for both</td></tr>
<tr><td>Purchase subsidies</td><td colspan="2">Excluded, as these are hard to predict over the next decade</td></tr>
<tr><td>VAT</td><td>Included for LPxx, excluded for LVxx</td><td>Excluded</td></tr>
<tr><td>Discount rate</td><td colspan="2">Personal perspective (LPxx): discount rate of 2.25% [30]
Business perspective (LVxx, HTxx, HBxx): discount rate of 8.0% [31]</td></tr>
</table>

[23] ICCT (2022). Assessment of light-duty electric vehicle costs and consumer benefits in the United States in the 2022-2035 timeframe.
[24] TNO (2022). Techno-economic uptake potential of zero-emission trucks in Europe tno_2022_r11862_techno-economic_uptake_potential_of_zero-emission_trucks_in_europe.pdf
[25] Rijkswaterstaat (2019). Routeradar 2019 Straatbeeldmonitor Wegvervoer Routeradar 2019 - Duurzame mobiliteit (rwsduurzamemobiliteit.nl)
[26] https://alternative-fuels-observatory.ec.europa.eu/consumer-portal/electric-vehicle-recharging-prices; data for November 2022
[27] Rijkswaterstaat (2020). Routeradar INNOM Marktontwikkeling Wegvervoer, Publicaties Routeradar - Duurzame mobiliteit (rwsduurzamemobiliteit.nl)
[28] RVO (2021). Handreiking Total cost of ownership (TCO)-berekening voor personenauto's Handreiking TCO-berekening voor personenauto's (rvo.nl)
[29] Transport & Environment (2022). A comparison of car taxation in Europe The good tax guide (transportenvironment.org)
[30] Rijkswaterstaat (2021). Factsheets Q&A discontovoet 2021 Factsheets Q&A discontovoet 2021 | Rapport | RWSeconomie.nl
[31] European Commission, JRC (2018). Heavy duty vehicle CO2 emission reduction cost curves and cost assessment – Enhancement of the DIONE model https://data.europa.eu/doi/10.2760/555936

Table 12: Costs for the VIPV for trucks and buses in 2023, 2025 and 2030

PV costs	2023	2025	2030
€/m²	132	119	112
Installation (cables etc.)	3000	2476	1878
Battery (HT2x only)	3700	3054	2317
Total	10000	8500	7000

Table 13: Costs for the VIPV for light duty vehicles in 2023, 2025 and 2030

PV costs	2023	2025	2030
€/m²	500	290	180
Installation	400	330	250

The information in Table 12 and Table 13 can be combined with the available PV area in Table 10 to calculate the total costs for the VIPV installations.

1.2.3. Fleet model

Initially, the project aimed to base projections of the European EV fleet on PRIMES-TREMOVE to ensure consistency with other EU studies. As these data were not available within the project timeframe, an alternative approach was applied for this analysis.

An alternative approach was developed, which in essence combines the Dutch historic and predictive EV fleet development curves with the present EU EV fleet to predict the future European EV fleet.

The Dutch EV fleet trend was taken from data and calculations underpinning the 'Klimaat- en Energieverkenning' (Explorative study climate and energy)[32]. Separate trends were available for passenger cars, vans, buses and trucks. For vans and trucks also a further breakdown was used.

The current EU27 EV fleet was taken from data from the European Alternative Fuel Observatory platform[33]. The current share of EVs in the fleet were was calculated using the total EU27 fleet size for each of the four categories of vehicles [ACEA; numbers for 2021 were the most recent ones at the moment].

The EU27 EV share for each of the four categories was matched with a point on the EV adoption timeline in the Netherlands. For example, for passenger cars, the current 1.3% in the EU matches approximately with the end of 2019 in the Netherlands. Subsequently, the uptake in Europe was assumed to follow the same pattern: if 2019 predicts for 2023, 2021 predicts for 2025 and 2026 (forecast) predicts for 2030.

Next the fleet was further broken down in the 23 archetypes. For the European fleet, sales numbers per vehicle model were requested from the EAFO consortium, and received for light duty vehicles. The models were categorised to the archetypes LP1x/LP2x/LP3x and LV1x/LV2x.

[32] PBL, TNO, CBS & RIVM (2022), Klimaat- en Energieverkenning 2022. PBL Netherlands Environmental Assessment Agency.

[33] https://alternative-fuels-observatory.ec.europa.eu

For LP14 an analysis was made of electric shared cars in Europe. That proved to be very hard to find or deduct, therefore the Dutch electric shared car fleet was extrapolated.

The split among the three mileage categories LPx1/LPx2/LPx3 is assumed to be 33%/33%/33%, because in the archetype definition the annual mileages were chosen in such a way that they represent 1/3 of the fleet each. The fleet size of LP11 is actually distributed 50/50 over LP10 and LP11.

The mileage of electric vans was limited up to end of 2021 for the most sold models, up to 150 km. This was used to make an assumed split between local and regional distribution vans (90/10 in 2023, 80/20 in 2025 and 50/50 in 2030).

For trucks and buses no manufacturer/model-specific numbers were available, therefore the split between rigid and tractor-trailer and bus and coach is based on assumptions. Trucks were split according to the Dutch EV fleet. Long-distance electric buses and trucks were set to zero in 2023.

This section demonstrated how vehicle-level energy efficiency measures, including VIPV, influence total cost of ownership and operational viability across vehicle archetypes. Moreover, it demonstrated how these effects translate into alternative pathways for the composition and uptake of the European EV fleet in 2025 and 2030.

Building on these fleet-level outcomes, Task 1.3 examines how different levels of vehicle energy efficiency affect recharging infrastructure deployment, grid integration, and local congestion pressures within the electricity system.

1.3 Potential impacts of different levels of energy efficiency of electric cars and trucks on recharging infrastructure deployment and integration into the electricity grid

The potential implications of VIPV on the development of charging infrastructure and the wider electricity system are assessed using a series of electricity system models at different resolutions. Two scenarios are explored: one where vehicles are connected to the grid as much as possible to enable optimal use of the EV (through vehicle-to-grid technology and smart charging), and one where only the charging needs of users are considered. We quantify the impact of VIPV and other efficiency improvements on total energy demand, the need for charging infrastructure at a local level, as well as impacts on peak loads in local networks and the potential savings in electricity distribution infrastructure. The quantification of these impacts is important, because energy efficiency improvements of EVs may help overcome barriers to large scale adoption of electromobility, such as local net congestion.

1.3.1. Neighbourhood charging demand

These issues would come from adding vehicle charging power demand to the power demand for other end uses and exceeding the local grid (transformer) capacity. The first step to do this is to determine what the charging demand is at the neighbourhood level.

From individual profiles to neighbourhood demand

The starting point is the collection of demand profiles as generated using the model described in paragraph 1.1.6. These profiles can be extracted from the time series output of the energy flow model (example data shown in Figures 8 -10), which specify the grid electricity demand for a given vehicle archetype in 10-minute intervals over a year. The first processing step on those profiles is to go from one vehicle to an average vehicle (for a group of vehicles of the same archetype) . This is done because the source profiles have a single specific arrival and departure times leading to very specific demand peaks. Instead, since vehicles will arrive and depart in time ranges, the average vehicle profile allows to smooth the demand curves. To do this, we spread the source profile demand across time intervals (evenly across ten 10-minute intervals both ways).

Defining neighbourhoods

To compute the total demand at neighbourhood level, we need to multiply each of these average profiles per archetype by the number of vehicles of that archetype that charge in the neighbourhood (see below for the parameters that define the neighbourhoods). We need to do this for all location types (base/home, work, fast, opportunity).

Our focus here is to see how charging demand for electric vehicles competes with demand for other end uses, so we look at situations where the capacity of the local grid is shared between charging vehicles and delivering power to other uses. For this reason, we do not look at cases involving fast charging or base charging of trucks and busses, as these will have a dedicated local grid infrastructure. We also start by looking at the case where the competition is the most prevalent, namely residential neighbourhoods, where only cars charge and they do so at their home/base (which can be on-street charging).

To determine how many cars of each type are charging, we need to multiply the amount of households in a neighbourhood with the following factors:

1) The number of cars per household (pulled from CBS statistics, with 0.4 cars per household in the urban neighbourhood (Amsterdam), 0.9 cars per household in the semi-urban neighbourhood (Hilversum), and 1.3 cars per household in the rural neighbourhood (De Fryske Marren)
2) The share of the car type in the car fleet. From the archetype construction data (see T 1.1), we have 42.5% SUVs, and 57.5% small and medium cars (which are themselves split 52%/48%)
3) The share of that car type with the kilometrage corresponding to that archetype. These will vary according to the neighbourhood type. For SUVs and medium cars, we assume that the three kilometrage levels have 25% and add 25% to one of the levels (low for urban, medium for semi-urban, low for rural). For small cars, we do something similar, except that we first attribute 10% to both the lowest and highest kilometrages (corresponding to occasional use and shared cars, respectively).
4) The percentage share of private/public charging (depending on the archetype). We assume that the percentage of private charging corresponds to the percentage share of free-standing and semidetached houses.
5) The vehicle electrification level. This will be our variable to test how much a neighbourhood can electrify its passengers cars (we use a 80% level to see what would happen with a large vehicle electrification level).

Configuration profiles

The charging demand generated above will depend on the chosen aspects of the vehicle configuration and use, which includes the charging strategy, the amount of solar panels on the vehicle (no, on roof, on roof and on the side), as well as the reserve level and parking hours. We can assume of mix of these to determine an average neighbourhood profile, or we can compare cases where all vehicles have a given configuration.

1.3.2. Demand fit to transformer capacity

Determining transformer capacity

Transformer size

In order to analyse the effect of VIPV on local infrastructure, we first calculate the capacities of electrical substations in archetypical neighbourhoods of the three types mentioned above. This is done by using actual data from a Dutch local infrastructure operator. This dataset consists of the number of connections for given substations, the number of total connections of the whole neighbourhood and the capacity of the substation.

We determine the substation capacity for three representative neighbourhood archetypes that match the rural, suburban and urban types. We chose the typical values of 2.30 kVA/household for the urban neighbourhood, 1.21 kVA/household for the semi-urban neighbourhood, and 3.52 for the rural neighbourhood (for each neighbourhood type, there are locations with significantly lower transformer capacities. To get the charging capacity (in kW per household), we need to multiply these by a power factor, which we set to 0.8, in accordance to discussions with experts.

Next, the capacity is scaled to neighbourhood level according to amount of connections per neighbourhood in the provided data. This capacity will be used to analyse the effects of VIPV on local infrastructure, by comparing instances of exceeding of capacity.

Determining demand from other activities

Statistical data for archetypical neighbourhoods in the Netherlands is used to determine the load profiles of from non-BEV energy users on local infrastructure. The generated profiles consist only of residential demand profiles from: five housing types in the three neighbourhood types rural, suburban and urban.

In order to determine the mix of housing types, data (CBS, 2023) from the Netherlands Enterprise Agency (RVO) is used, consisting of the relative shares of five housing types for each province in the Netherlands. These types are multi-family, terraced, corner, semi-detached and detached houses.

Additional data (CBS, 2023) from CBS is used, containing electricity use for specific archetypical municipalities in the Netherlands, split up in housing types. We assign the neighbourhood types rural, suburban and urban to three of them, and combined with the housing type data, have a relative share of housing type and accordingly yearly electricity use, to be multiplied with the number of connections in archetypical neighbourhoods of the substation capacity estimation.

Finally, to get a temporal profile of the electricity use, MFFBAS[34] standard consumption profile E1A is used for all housing types. It is an average, normalised consumption profile, based on measurements for home connections of <= 3x25A.

This section quantified how vehicle-level energy efficiency improvements, including VIPV, can reduce neighbourhood-level charging demand, alleviate peak loads, and lower local grid congestion and infrastructure requirements.

Section 1.4 builds on this system-level analysis by presenting the irradiance and energy consumption simulation results that underpin the assessed impacts of VIPV across vehicle archetypes and regions.

1.4 Irradiance and Energy Consumption Simulation Results

This paragraph presents the results of the Energy Flow Model, which simulates the annual energy balance of electric vehicles. The analysis compares scenarios without PV, with PV on sun-facing surfaces, and with full PV coverage, highlighting the impact of vehicle-integrated photovoltaics (VIPV) on reducing grid energy demand and charging frequency. Results are shown for all vehicle archetypes under Amsterdam and Madrid conditions, providing insights into PV contribution, seasonal effects, and efficiency improvements across different usage patterns.

1.4.1. Results Energy Flow Model

Energy flows over the year

As described above, the energy flow model calculates the SoC of the battery, taking into account the charging and the energy needed for the vehicle to operate: propulsion, HVAC and other auxiliary systems.

The graphs below show an example of the output of the energy flow model for the small passenger car with occasional use (LP12). Figure 9 shows the situation without PV, Figure 10 for PV on the sun facing surfaces and Figure 11 for PV on all surfaces.

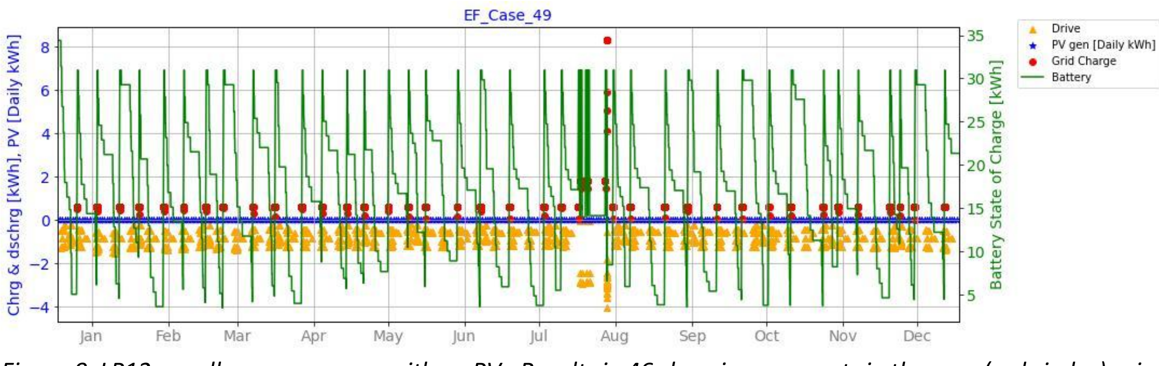


Figure 9: LP12, small passenger car, with no PV - Results in 46 charging moments in the year (red circles) using charging strategy A

[34] Joint platforms of the Dutch energy sector 'Market Facilitation Forum' & 'Beheerder afsprakenstelsel' (MFFBAS), www.mffbas.nl/en

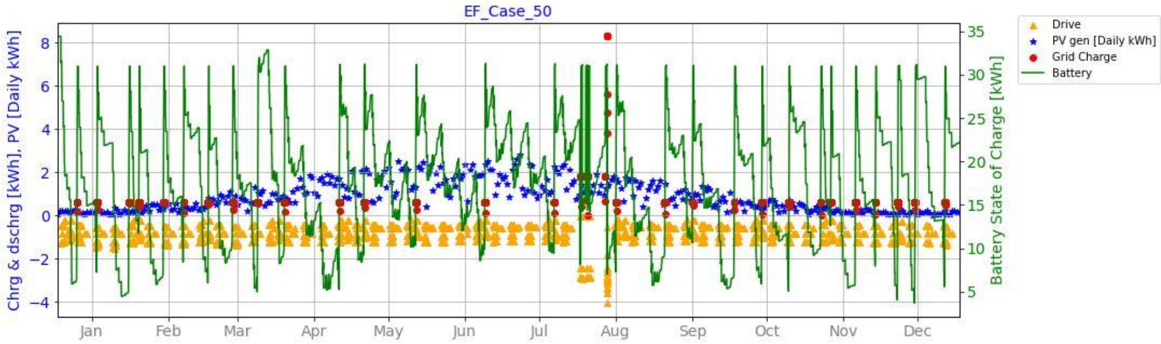


Figure 10: LP12, small passenger car, with PV on sun facing surfaces – Results in , far less charging moments, especially in summer. In total 36 charging moments in the year using charging strategy A.

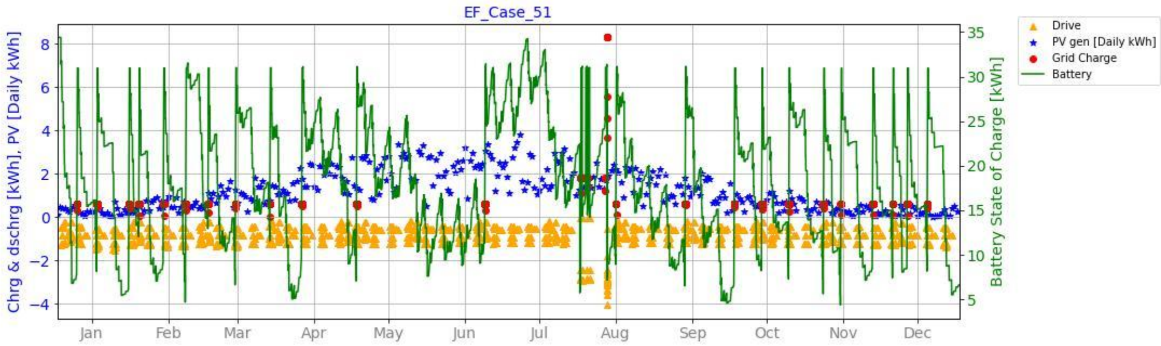


Figure 11: LP12, small passenger car, with PV on all surfaces - . The number of charging moments is further reduced to 31 for the year

In blue, the energy generated by the PV is depicted, in green the battery SoC (right axis) and in orange the energy needed for driving. The red dots indicate the charging moments. When PV is introduced to this archetype the battery state of charge is higher during the summer months and the number of charging moments is reduced strongly.

With this data, the reduction in the number of charging moments and the reduction in the amount of energy needed from the grid can be determined. See more examples in Appendix D. This is done for all archetypes based on the energy consumption of the different archetypes in 2023 configuration. An extensive overview is given in Appendix E. The resulting share of the vehicle's total energy demand that is covered by the PV yield is indicated in Figure 12 for Amsterdam and Figure 13 for Madrid. The selected charging strategy is A (conservative lookahead).

Depending on the trip type distribution (shading can affect the yield), PV can provide electricity for a number of km per year. For instance, the difference between the PV contribution for LP12 and LP13 is almost completely due to a higher mileage of LP13. On the other hand, for LP10 and LP11, the PV could not be fully utilized due to extended times where the vehicle is stationary, and the battery is full. This caps the effective contribution.

Heavy-duty vehicles have a less favourable ratio of *PV area / energy consumption per km*, and generally have high annual mileages. As a result, the share of the vehicle's total energy demand that is covered by the PV yield is relatively low.

For Madrid, unless utilization becomes limiting (LP10), the contribution of PV is around 1.5 times the value for Amsterdam for all archetypes.

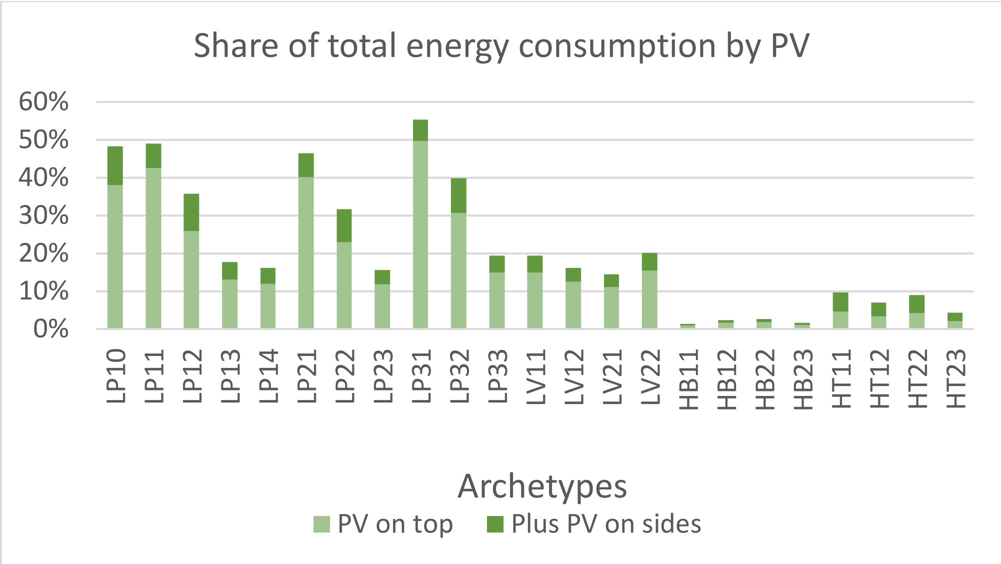


Figure 12: Share of total energy consumption provided by PV of each archetype (Amsterdam)

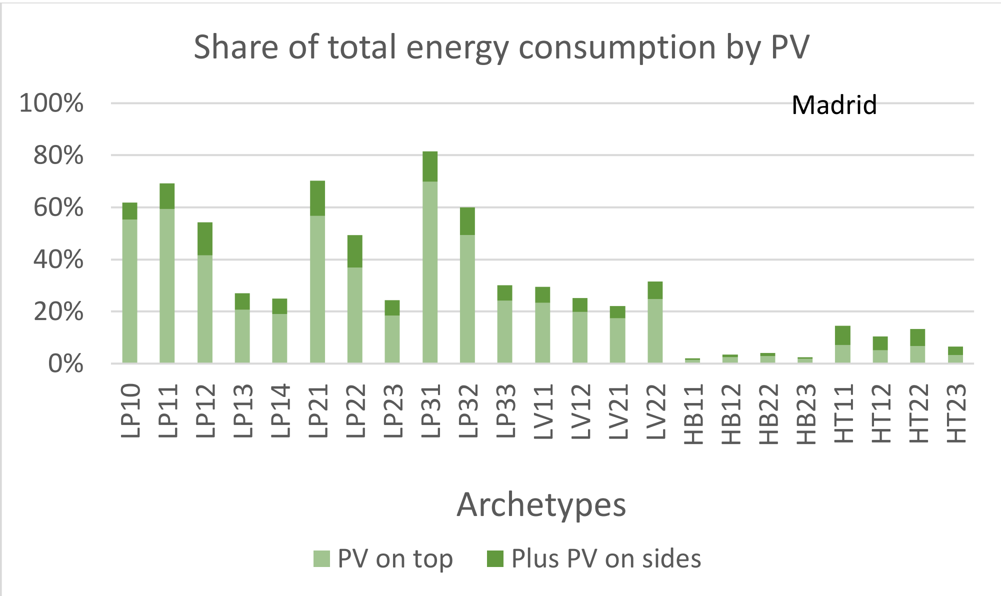


Figure 13: Share of total energy consumption provided by PV of each archetype (Madrid)

1.4.2. Energy efficiency impacts on EU fleet composition

Energy consumption reduction

In order to study the effect of the use of VIPV on the needed grid capacity in the future, different

energy improvement scenarios have been identified. Table 14 and Table 15 give an overview of the energy improvement options that are considered for electric passenger cars. A cost calculation was performed as described in paragraph 2.2.1 for all these improvements to see if they are cost effective in 2025 and in 2030. In Table 14 and Table 15 it is indicated which options are found to be cost effective for which archetypes as well. The final column indicates the *Ultimate* scenario in which all the efficiency improvement options are implemented.

Table 14: Cost-effective efficiency improvements options as identified for small passenger cars

Name	Description	2025					2030					Ultimate				
		LP10	LP11	LP12	LP13	LP14	LP10	LP11	LP12	LP13	LP14	LP10	LP11	LP12	LP13	LP14
TYRES1	Low rolling resistance tyres grade B	x	x	x	x	x										
TYRES2	Low rolling resistance tyres grade A						x	x	x	x	x	x	x	x	x	x
AERO1	Decrease tyre width to 175 mm						x	x	x	x	x	x	x	x	x	x
AERO2	Shutter grill											x	x	x	x	x
AERO3	Closed rims				x	x				x	x	x	x	x	x	x
AERO4	Flat floor											x	x	x	x	x
AERO5	Boat tail											x	x	x	x	x
MASS1	2025 glider mass reduction				x	x				x	x	x	x	x	x	x
MASS2	2030 glider mass reduction											x	x	x	x	x

Table 15: Cost-effective efficiency improvements options as identified for medium passenger cars and SUV's

Name	Description	2025						2030						Ultimate					
		LP21	LP22	LP23	LP31	LP32	LP33	LP21	LP22	LP23	LP31	LP32	LP33	LP21	LP22	LP23	LP31	LP32	LP33
TYRES1	Low rolling resistance tyres grade B	x	x	x	x	x	x												
TYRES2	Low rolling resistance tyres grade A							x	x	x	x	x	x	x	x	x	x	x	x
AERO1	Decrease tyre width to 175 mm							x	x	x	x	x	x	x	x	x	x	x	x
AERO2	Shutter grill									x			x	x	x	x	x	x	x
AERO3	Closed rims			x			x			x			x	x	x	x	x	x	x
AERO4	Flat floor													x	x	x	x	x	x
AERO5	Boat tail													x	x	x	x	x	x
MASS1	2025 glider mass reduction			x	x	x	x			x	x	x		x	x	x	x	x	x
MASS2	2030 glider mass reduction												x	x	x	x	x	x	x

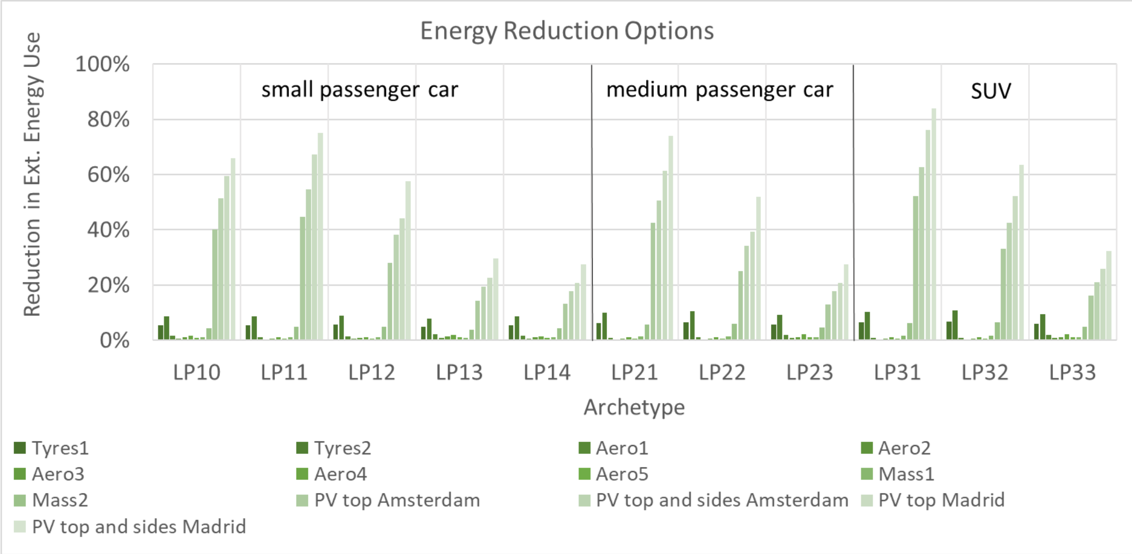


Figure 14: Reduction in external energy consumption for passenger cars relative to the energy consumption of the Amsterdam baseline vehicle

Figure 14 shows the reduction in energy consumption relative to 2023 energy consumption for Amsterdam. Except for the PV on top and PV on top and sides for Madrid, which are compared to the Madrid 2023 vehicle energy consumption. The 2023 energy consumption for Madrid is slightly higher than for Amsterdam due to the increased temperatures and related airco consumption. As a result, the reduction in energy consumption of the non-PV options for Madrid will be slightly lower (not shown). As can be seen in this figure, the reduction in energy consumption from PV is by far the highest for all passenger car types when compared to the other energy reduction options. When looking within an archetype (e.g. LP10 to LP14), the effect of the improvement due to the PV is reducing with increasing use pattern number This is due to the fact that the annual driving distance increases from LPx0 to LPx4 while the PV reduction is a fixed contribution that depends on the surface area of the PV. As a result the relative effect of PV on total energy consumption decreases with increasing annual driving distance.

It is noteworthy that part of the reduction in external energy consumption resulting from PV is in the fact that the charging losses are lower for PV charging. Every kWh charged with PV avoids approximately 1.1 kWh from the grid, because costly AC to DC conversion losses are avoided.

Improving the efficiency of the onboard charger is actually an additional energy consumption reduction measure that was not included in the calculations. As described previously the loss is kept constant at 15%. However, since charging losses are included in the WLTP energy consumption, there is an incentive for manufacturers to reduce these losses. The losses are already quite different among manufacturers/models; it seems that 10% is certainly possible. That would reduce the AC grid energy consumption by 5%. Note that the actual losses also depend on the charging speed. Also, a lot of fast charging and/or VIPV charging would reduce the reduction effect, as AC charging is less needed.

Table 16: Cost-effective efficiency improvements options as identified for vans

Option	Description	2025				2030				Ultimate			
		LV11	LV12	LV21	LV22	LV11	LV12	LV21	LV22	LV11	LV12	LV21	LV22
TYRES1	Low rolling resistance tyres	x	x	x	x								
TYRES2	Low rolling resistance tyres 2030					x	x	x	x	x	x	x	x
AERO1	Decrease tyre width to 175 mm					x	x	x	x	x	x	x	x
AERO2	Shutter grill	x	x	x	x	x	x	x	x	x	x	x	x
AERO3	Closed rims	x	x	x	x	x	x	x	x	x	x	x	x
AERO4	Flat floor									x	x	x	x
AERO5	boat tail									x	x	x	x
MASS1	2025 glider mass reduction	x	x	x	x								
MASS2	2030 glider mass reduction					x	x	x	x	x	x	x	x

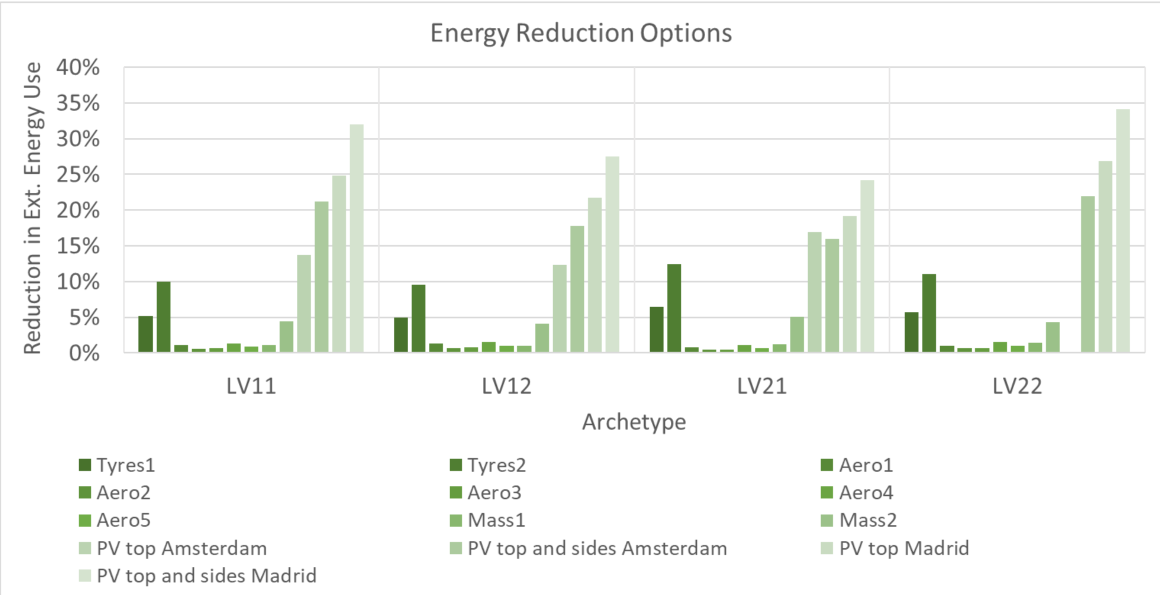


Figure 15: Reduction in external energy consumption for vans relative to the energy consumption of the Amsterdam baseline vehicle.

For vans (Figure 15) the effect of the energy reduction options shows similar trends as for the cars. The effect of PV is somewhat lower than for most passenger cars. On the one hand the PV surface area is larger, but on the other hand the annual mileages are higher, and the energy consumption per km as well.

Table 17: Cost-effective efficiency improvements options as identified for trucks

Option	Description	2025				2030				Ultimate			
		HT11	HT12	HT22	HT23	HT11	HT12	HT22	HT23	HT11	HT12	HT22	HT23
TYRES 1/2	Low rolling resistance tyres on truck/tractor	x	x	x	x	x	x	x	x	x	x	x	x
TYRES 3/4	Tyre pressure monitoring system (TPMS) on truck/trailer	x	x	x	x	x	x	x	x	x	x	x	x
TYRES 7	Wide base single tyres					x	x	x	x	x	x	x	x
AERO2	Side and underbody panel at truck chassis					x	x	x	x	x	x	x	x
AERO3	Aerodynamic mud flaps			x	x	x	x	x	x	x	x	x	x
AERO5	Redesign, longer and rounded vehicle front			x	x			x	x			x	x
AERO6	Side and underbody panels at trailer chassis			x	x			x	x			x	x
AERO7	Boat tail short, additional							x	x			x	x
AERO8	Retrofittable roof and rear recess flaps 400 mm			x	x			x	x			x	x
MASS1	5% Mass reduction (truck/tractor)					x	x	x	x	x	x	x	x
AUX1	Electric hydraulic power steering			x	x			x	x			x	x
AUX2	LED lighting							x				x	
AUX3	Air compressor	x	x	x	x	x		x	x	x		x	x
AUX4	Cooling fan							x	x			x	x

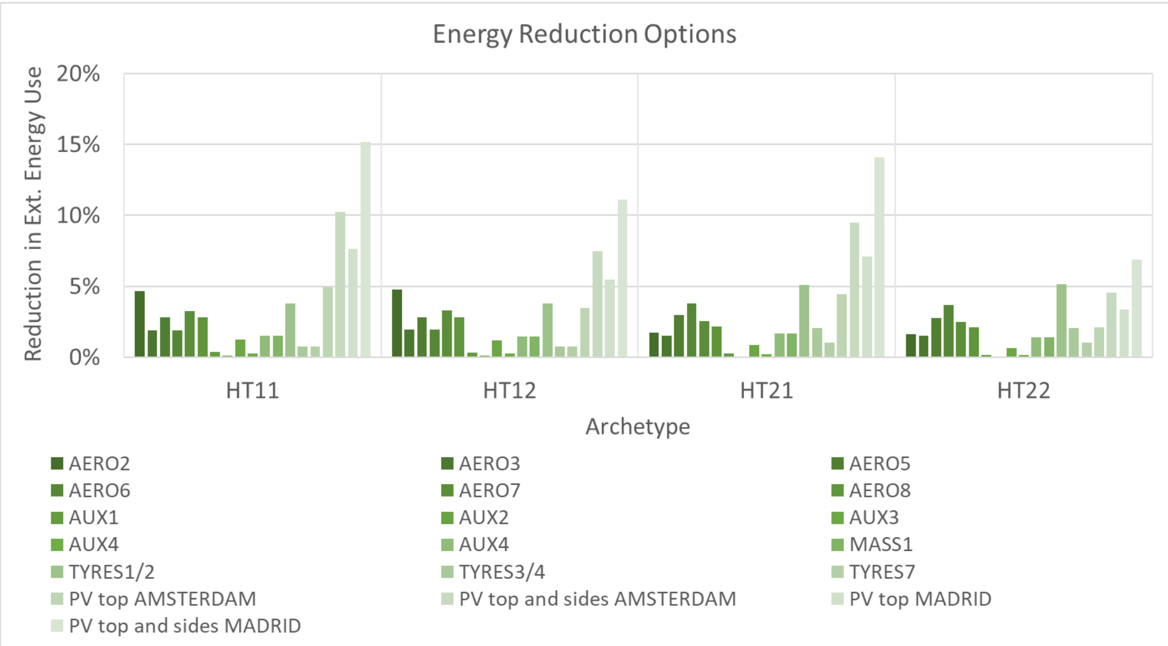


Figure 16 Reduction in external energy consumption for trucks relative to the energy consumption of the Amsterdam baseline vehicle

Trucks have a much larger PV area, but also a larger energy consumption and annual mileage. This results in a relatively low effect of VIPV on the energy reduction, but still in the same order of magnitude as that of the other energy reduction options, see Figure 16.

For busses, the mileage is on the same order of magnitude as for trucks, but the area for PV is much lower. The area for the sun facing PV e.g. is for buses 8 m^2 whereas for the truck 14 m^2 is available. The result is a much lower energy reduction from adding PV on busses compared to trucks. For the PV on the sides, the effect is even larger, as the busses have windows on the side and have ample area for PV. As a result, there is only minor improvement from adding PV on the sides in the bus cases, see Figure 17.

Table 18: Cost-effective efficiency improvements options as identified for buses

Option	Description	2025				2030				Ultimate			
		HB11	HB12	HB22	HB23	HB11	HB12	HB22	HB23	HB11	HB12	HB22	HB23
TYRES1	Low rolling resistance tyres on truck/tractor	x	x	x	x	x	x	x	x	x	x	x	x
TYRES3	Tyre pressure monitoring system (TPMS) on truck/trailer					x	x	x	x	x	x	x	x
TYRES7	Wide base single tyres					x	x	x	x	x	x	x	x
MASS1	Side and underbody panel at truck chassis	x	x	x	x	x	x	x	x	x	x	x	x
MASS2	Aerodynamic mud flaps					x	x	x	x	x	x	x	x
MASS3	Redesign, longer and rounded vehicle front	x	x	x	x	x	x	x	x	x	x	x	x
TOT1	Side and underbody panels at trailer chassis									x	x	x	x
TOT2	Boat tail short, additional									x	x	x	x
TOT3	retrofittable roof and rear recess flaps 400 mm									x	x	x	x
TOT4	5% Mass reduction (truck/tractor)									x	x	x	x
AUX1	Electric hydraulic power steering												
AUX3	LED lighting												

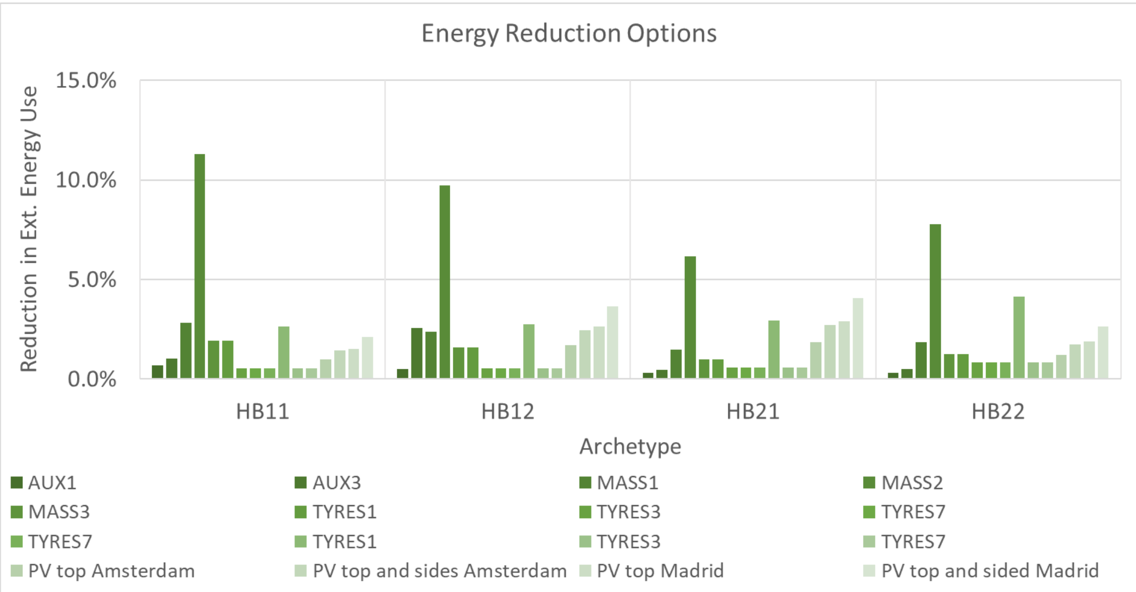


Figure 17: Reduction in external energy consumption for busses relative to the energy consumption of the Amsterdam baseline vehicle

Results from TCO analysis

The TCO was calculated for a period of 5 years for each vehicle archetype, irrespective of their annual mileage. The five years represent the (average) time period that the vehicle is with the first owner. It is at purchase that decisions are made that determine the uptake rate of new features on vehicles. Figure 18 shows the TCO for the passenger vehicle archetypes for all the possible modelled levels of efficiency improvements (For the other archetypes, see Appendix F).

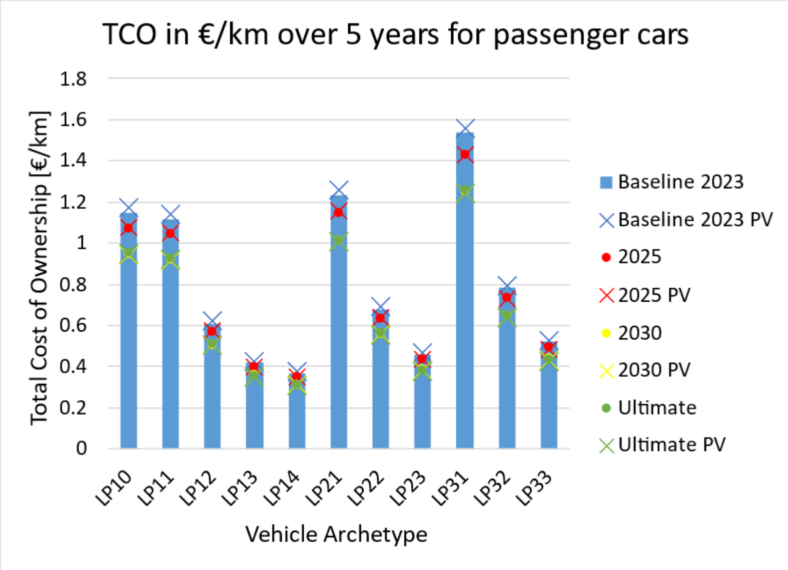


Figure 18. Total cost of ownership in euros per kilometre for different vehicle passenger car archetypes and different scenarios based on their efficiency improvements for an ownership period of 5 years

It can be seen that the total cost of ownership of vehicles is highly dependent on the mileages they drive. The vehicles that drive less kilometres have a higher cost per kilometre than those that drive more, because: a) depreciation has a large share in the total costs over five years, b) depreciation is mostly dependent on time rather than mileage, and c) the contribution of energy costs is small for the first owner. This is visible in the case of LP10, LP11, LP21 and LP31 as compared to the others. It can also be seen that the lighter vehicles that drive the most kilometres are the most cost-efficient (see LP13, LP14). Also, heavier SUVs' (LP33) seem to be relatively economical. This can be attributed to the assumed high mileage.

As for the VIPV, the cost improvements are the largest for vehicles with a low annual mileage. If the electricity generated by the VIPV installation is utilized to a large extent, which is the case for all archetypes, the relative contribution of it to the costs per kilometre becomes less at high mileages: once all VIPV generated electricity is used, one simply has to charge more off the grid, raising the average costs per kilometre. Ameliorating this effect is the lower average driving speeds for low-mileage vehicles. The amount of energy saved by VIPV is seen more visibly in these vehicles (LP10, LP11, LP21, LP31) than those that drive more and do more long distance trips (LP13, LP14, LP23, LP33). Although it does not seem to be economically beneficial to apply VIPV in 2023 for the lighter vehicles, it almost breaks even for the larger SUVs. But this difference is not very substantial. It can also be seen that the improvements of from applying PV in the ultimate scenario are more prominent for LP31 than for LP21. This is because of more area of PV available on these vehicles.

In general from Figure 18 it can be concluded that although the a VIPV vehicle is more expensive to buy, its costs per kilometre over the first five years are almost equal to those of a non-VIPV electric vehicle. The graphs in Appendix F show that the same is true for busses, vans and trucks. In 2030 this will be slightly more favourable still, because of improved VIPV efficiency and reduced costs.

A similar TCO analysis can be done for the lifetime of the vehicle, which is 18 years in Europe. Figure 19 shows the TCO for a vehicle owned for 18 years and how it compares to for the different packages of efficiency improvements.

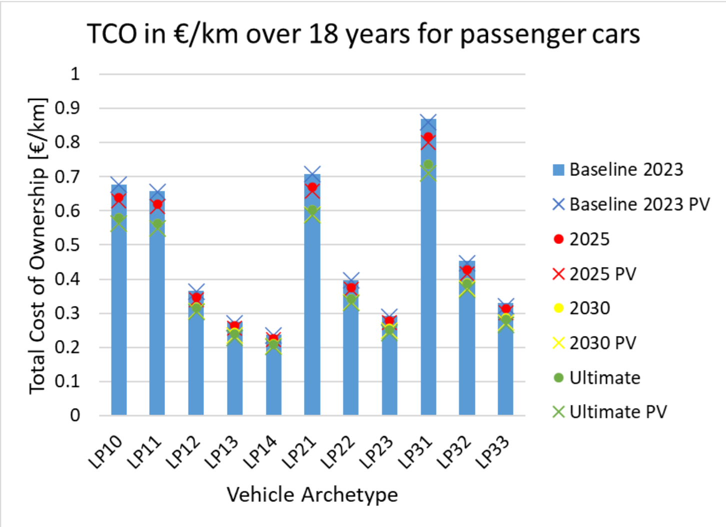


Figure 19: Total cost of ownership in euros per kilometre for different passenger car archetypes and different scenarios based on their efficiency improvements for an ownership of 18 years

It can be observed that over the entire vehicle lifetime, the addition of VIPV is economically viable for each of the archetypes. It can also be seen that the range in cost improvements also reduces. I.e., the improvement of the ultimate case with VIPV as compared to the baseline 2023 case is smaller for the lifetime of the vehicle as compared to the first ownership period of 5 years. This is clearly visible, in the case of LP31 where for 18 years of ownership of the vehicle, the improvement amounts to about 0.17 €/km whereas in the 5 year ownership period, this is 0.35 €/km.

For passenger cars the electricity costs have a small share in the total costs of ownership over the first 5 years: 4% for LP31 up to 17% for LP13 and LP33. For long-haul trucks it is a different story: electricity costs amount to 48% of the TCO. In other words, doubling of the charging costs would raise the km-costs of the vehicle by 48%. And while the effect of VIPV remains small, due to its small contribution to the total energy consumption, the energy reduction options are much more effective in reducing the costs than at the prices taken in the baseline.

1.4.3. Grid electricity consumption

The results of paragraph 0 on cost effective energy reduction options for 2025 and 2030 combined with PV were used to calculate the changes in TCO, but also to calculate the reduction in grid energy consumption in 2025 and 2030. The result is shown Figure 20 for the passenger cars and compared with the current situation without PV or other improvements and with the current situation with only PV and no other improvements.

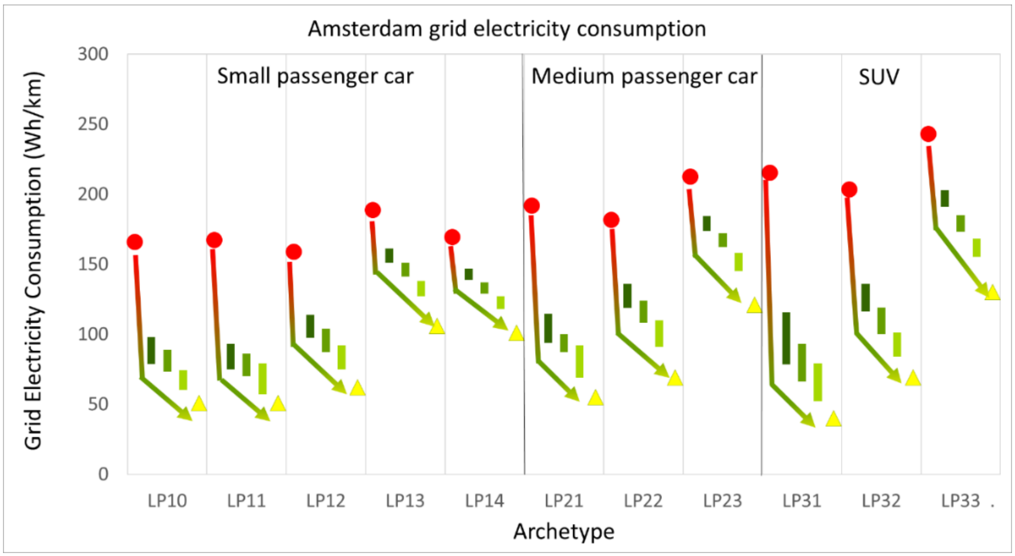


Figure 20: Amsterdam grid electricity consumption for an electric passenger car

Table 19: Legend for Figures 20-23

●	***2023 situation without PV***
▬	***2023 situation with PV for various charging strategies***
▬	***2025 situation with PV using cost effective energy consumption reduction options for various charging strategies using a PV efficiency of 21%***
▬	***2030 situation with PV using cost effective energy consumption reduction options for various charging strategies using an increased PV efficiency of 23%***
△	***the ultimate situation with the best energy reduction options combined for 2030 using an increased PV efficiency of 26%***

The energy reduction options that were used in the calculation can be found in Table 14 and Table 15. Arrows are a guide to the eye.

A clear drop in grid electricity consumption is seen when PV is added to the passenger cars and a further steady decrease is observed when applying the 2025 and 2030 energy reduction options from Table 14 and Table 15 . In general, for these passenger cars, the electricity consumption can be reduced by about 60-70% compared to the present situation. By combining all the energy consumption reduction options for the specific archetype, i.e. the ‘ ultimate’ scenario of Table 14 and Table 15, an additional reduction can be achieved, but those are not viable from a cost perspective.

Also for the vans a substantial drop in grid electricity consumption is observed, but the initial drop by adding PV is on the order of 30%, see Figure 21. Adding the cost-effective energy reduction options results in an additional reduction for both 2025 and 2030.

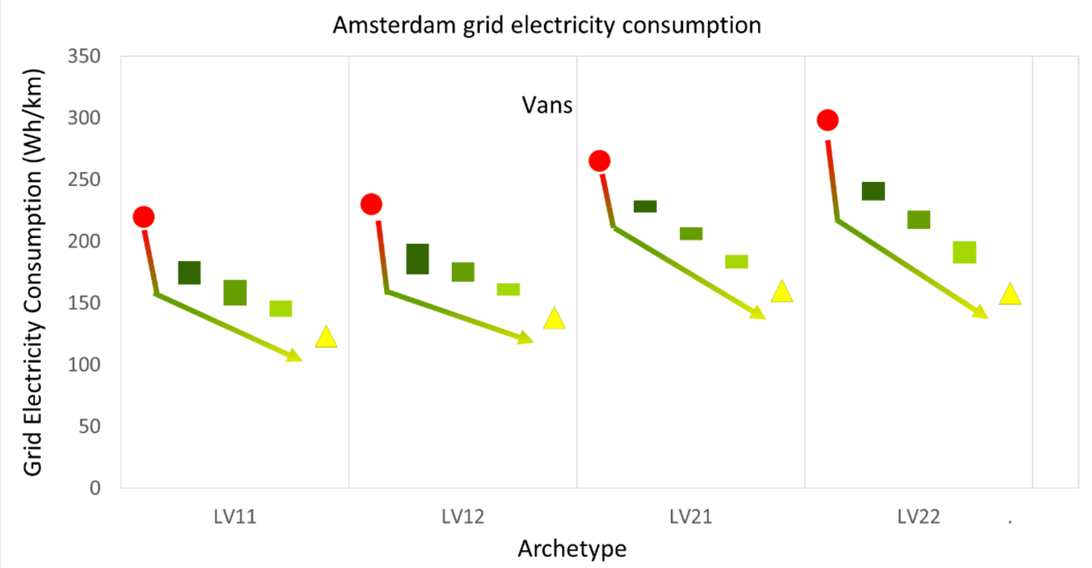


Figure 21: Amsterdam grid electricity consumption for an electric van

In Figure 22 it is seen that adding PV on truck results in only a small energy reduction option that is of a similar order of magnitude as the other improvement options. This is also seen in Figure 23 for the buses, where the initial reduction in grid electricity consumption from adding PV is much smaller compared to the reduction seen for cars and vans. But the downward trend upon adding PV and the other energy reduction options is clear and although relatively small compared to the original grid electricity consumption, the absolute values are much higher.

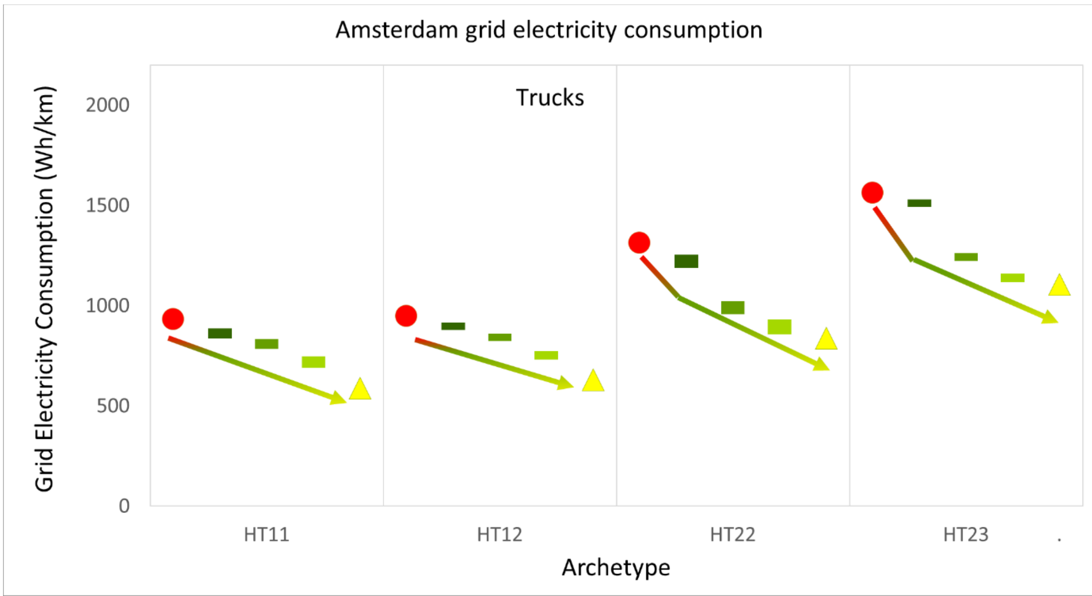


Figure 22: Amsterdam grid electricity consumption for an electric truck

Similar results are obtained for buses (Figure 23).

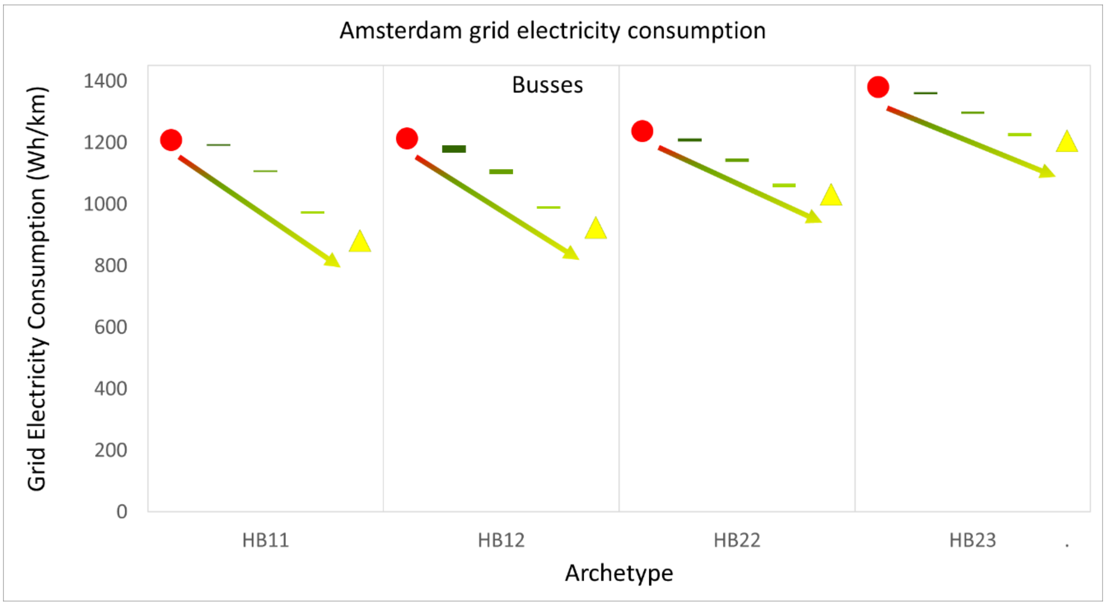


Figure 23: Amsterdam grid electricity consumption an electric bus

1.4.4. Results fleet model

The present battery electric vehicle fleet in Europe is 3.30 million vehicles, consisting of 3.28 million light duty vehicles (M1+N1) out of a total fleet of around 279 million LDVs (M1+N1), 11,673 buses and 3,739 trucks.

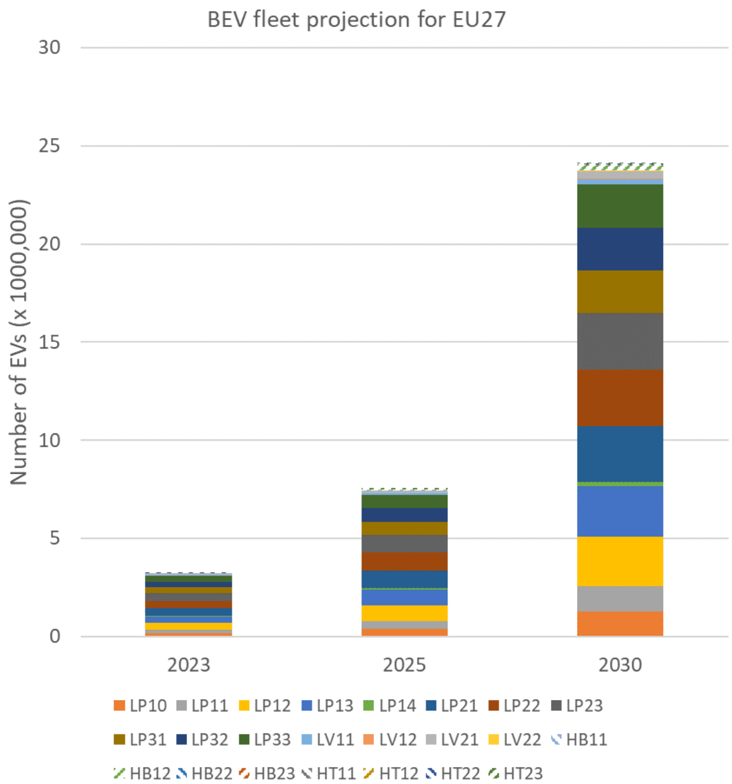


Figure 24: EU27 EV fleet in 2023 and projection for 2025 and 2030, broken down in SolarMoves archetypes

A projection has been made for 2025 and 2030, based on the historical and projected development of the EV fleet in the Netherlands; see Figure 24. The electrification rate used in the graph corresponds to the following values, see Table 20.

Table 20: Share of battery electric vehicles in the EU27 fleet in 2023 and projection for 2025 and 2030, per vehicle segment

Vehicle category	2023	2025	2030
Passenger cars	1.2%	2.8%	8.5%
Vans	0.4%	0.8%	2.2%
Buses	1.6%	11.4%	40.6%
Trucks	0.1%	0.1%	1.1%

Vehicle integrated PV and other energy consumption reducing measures for EVs can potentially reduce the grid electricity consumption by the EV fleet. Figure 25 shows, for a fleet as in Figure 24, the potential electricity consumption reduction if all EVs from 1/1/2024 onwards would be equipped with the economically viable energy efficiency options for 2025 or 2030. On top of that, it shows the potential of having VIPV in all EVs sold from 1/1/2024. The numbers shown are expressed as GWh per year.

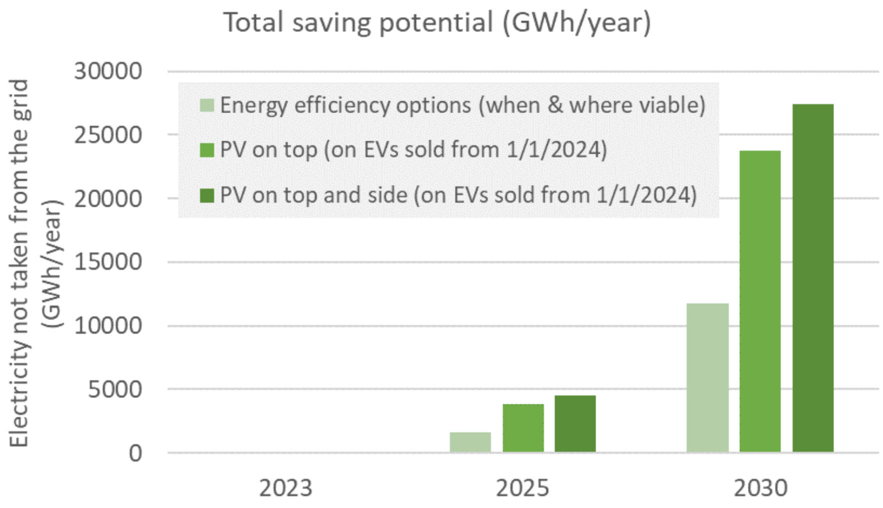


Figure 25: Potentially avoided grid electricity consumption resulting from reduced energy consumption options and VIPV, for the projected EV fleet, EU27. Baseline=2023 vehicle efficiency & no VIPV. Additional fleet only = only newly sold vehicles from 1/1/2024 onwards

The contribution of the different vehicle archetypes to this potential grid consumption reduction is shown for 2030 in Figure 26. The potential of energy efficiency improving options for an archetype depends on fleet size, annual mileage, speed profile and the effect of the combined measures. The potential of VIPV is dependent on a combination of fleet size, PV utilization grade and effectiveness of energy efficiency measures. A faster uptake of EVs of a certain archetype would increase its absolute reduction potential.

Based on the greenhouse gas emission intensity of electricity in the EU27 in 2022 and the indicative level for 2030 according to EEA, the greenhouse gas reduction as compared to the same EV fleet without VIPV and energy saving innovations, was calculated for the situation described above (all new vehicles have the viable energy efficiency options as well as VIPV), see Table 21.

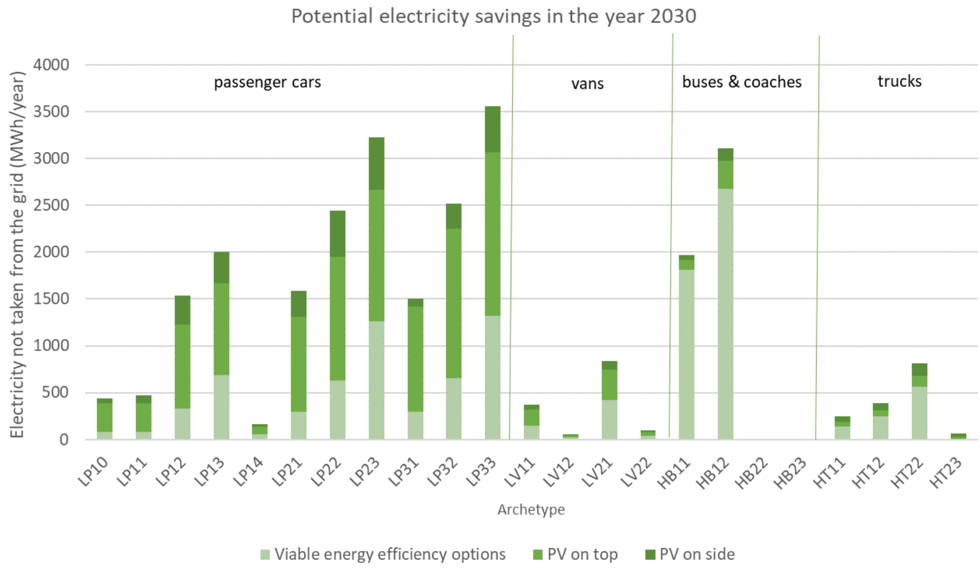


Figure 26: Contribution of the different vehicle archetypes to the potential electricity savings in 2030 for the vehicle archetypes

Table 21: Potential greenhouse gas emission reduction by energy efficiency and VIPV in the year 2025 and 2030

Year	Greenhouse gas emission reduction (kton CO_2-eq / year)		
	Viable energy consumption reduction options	Viable energy consumption reduction options plus PV on top (vehicles after 2023 only)	Viable energy consumption reduction options plus PV on top and sides (vehicles after 2023 only)
2025	340	814	957
2030	1342	2711	3123

Considering the starting points explained throughout this chapter, it is as expected that the CO_2 emission reduction potential is much larger in 2030 than in 2025: the EV fleet size is much larger in 2030 and a larger package of energy consumption reduction options is viable in 2030. Moreover, with respect to the potential of VIPV, it was assumed that all EVs from 1/1/2024 would be fitted with VIPV, which leads to a much larger share of VIPV vehicles in 2030 than in 2025. An interesting result in Table 21 is that PV on the top results in quite a step in greenhouse gas emission reduction, but that the additional effect of PV on the sides is quite small. Except for the trucks, the yield of PV on the sides is around 30% of that of the top. For low-mileage archetypes it can be as low as 14%, because the additional electricity cannot be stored for a part of the year.

This section presented the irradiance and vehicle energy-flow simulation results underpinning VIPV impacts, translating archetype-level PV yield and efficiency options into changes in charging events, grid electricity consumption, fleet-level electricity savings, and associated CO_2 reductions.

Section 1.5 builds on this quantified energy and charging profiles to assess how VIPV and efficiency improvements affect recharging infrastructure needs. A specific focus is placed on the local capacity constraints and peak loads that drive grid congestion.

1.5 Model results on impact on recharging infrastructure

This paragraph examines the impact of Battery Electric Vehicle (BEV) charging demand on local electricity grids, where capacity is constrained by neighbourhood transformer limits. The analysis compares BEV charging requirements—both with and without vehicle-integrated photovoltaics (VIPV)—against non-BEV demand to determine whether combined loads exceed transformer capacity. Results are presented for three Dutch neighbourhoods under an 80% electrification scenario, highlighting the influence of VIPV on reducing local demand and mitigating congestion risks. Seasonal variations and the role of grid capacity enhancements are also explored to assess the effectiveness of VIPV in alleviating infrastructure challenges.

1.5.1. Neighbourhood charging demand

Neighbourhood electricity supply is limited by the local transformer capacity. Problems arise when demand exceeds this capacity. Therefore, the first analysis assess the comparative charging demand of Battery Electric Vehicles (BEVs) in relation to the demand for alternative end uses (non-BEV demand), and ascertains whether their combined requirements fall within the local transformer capacity. This is also done in the case that all BEVs are equipped with VIPV technology.

A collective charging strategy or a predefined combination of charging strategies needs to be established for battery electric vehicles (BEVs) equipped with and without VIPV. This approach is essential for the purpose of isolating the impact associated with the installation of VIPVs. The ensuing outcomes pertain specifically to Charging Strategy A.

The results for three Dutch neighbourhoods are presented in Figure 27 as the distribution of the ratio of BEV charging demand to non-BEV demand for 10 minute intervals throughout the year. These figures correspond to a vehicle electrification rate of 80%, a deliberate choice positioned at the upper limit of projected electrification rates in the ensuing years, thereby facilitating an examination of outcomes under substantial electrification scenarios. Note that the time intervals when no BEV charging occurs are omitted for scale and clarity. Installation of VIPVs results in a reduction in demand at a local level, as previously outlined in paragraph 1.4.3 at the vehicle and full EU fleet level.

The depicted figures yield two noteworthy observations. Firstly, they indicate that, for the majority of instances, the BEV charging demand is significantly less than demand for alternative purposes, even under the elevated electrification rate selected for this analysis. Secondly, the figures demonstrate that the incorporation of VIPVs perceptibly diminishes the BEV charging demand in contrast to non-BEV demand. This observation substantiates the existing understanding that the installation of VIPVs results in a reduction in demand at a local level, as previously outlined in paragraph 1.4.3 at the vehicle and full EU fleet level.

The influence of VIPV exhibits a pronounced temporal dimension. Notably, the impact of VIPV is relatively modest during the fall and winter seasons, whereas their influence during the summer and spring months is markedly more substantial when compared to the overall annual perspective, as illustrated in Figure 28. This is particularly true for smaller charging events (up to a 0.50 ration of BEV to non-BEV demand at the same moment).

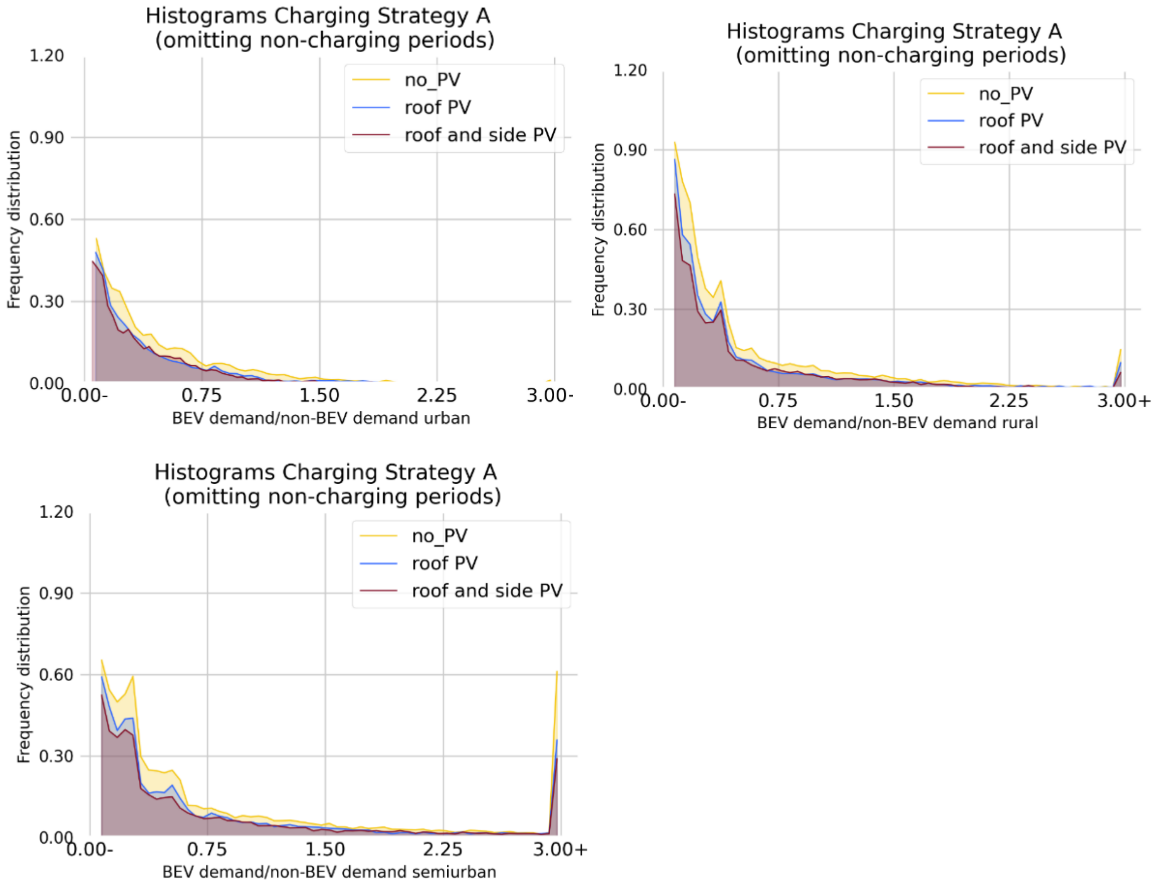


Figure 27: BEV/non-BEV demand frequency distribution for the three neighbourhoods (urban (top left), rural (top right), semiurban (bottom left)) in The Netherlands and Charging Strategy A, with the first bin removed for visibility reasons

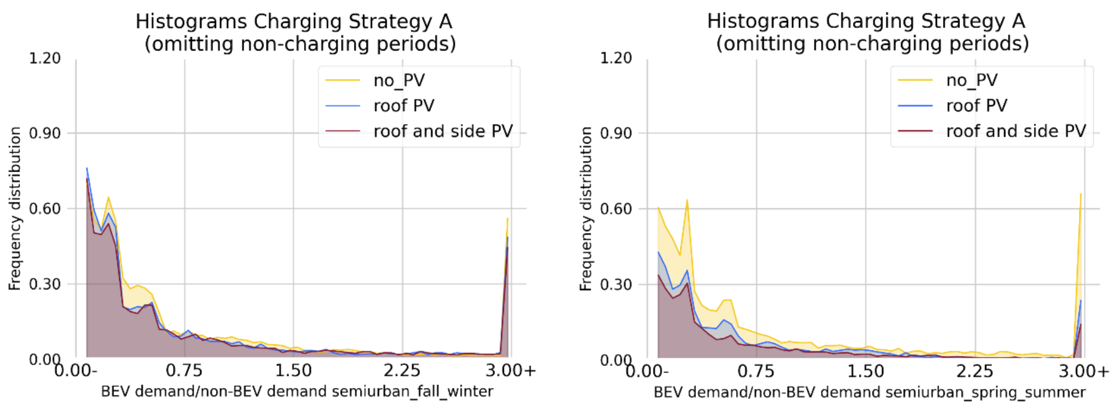


Figure 28: Seasonal comparison of BEV/non-BEV demand frequency distribution for the semiurban neighbourhood in The Netherlands and Charging Strategy A, with the first bin removed for visibility reasons. The comparison is for Fall-Winter (left) and Spring-Summer (right)

The discernible influence of VIPV on the local grid necessitates a nuanced exploration of efficacy in mitigating congestion challenges. To elucidate this, it is imperative to introduce two critical variables into our analysis: the precise numerical value of total demand, as opposed to the represented ratio, and an evaluation of its relationship with the neighbourhood transformer capacity.

Total demand is calculated by adding demand profiles for other purposes to the charging profiles in each neighbourhood and subtract the local transformer capacity, following the procedures explained in paragraph 1.3. This results in a time series depicting the differential between total demand and transformer capacity. This time series is visually represented in the form of a histogram, in Figure 29.[35]

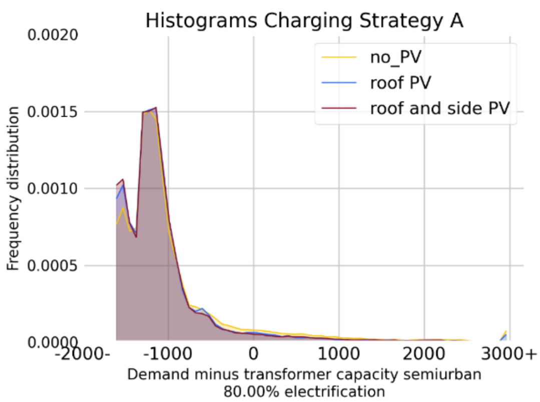


Figure 29: Demand minus transformer capacity frequency distribution for the urban neighbourhood in The Netherlands and Charging Strategy A, at 80% electrification

The introduction of a large number of EVs in a neighbourhood, can result in significant grid congestion problems. For instance, in a semi-urban Dutch neighbourhood with an 80% electrification rate, such instances occur in approximately 9% of the analysed time intervals.

Furthermore, the analysis also reveals a discernible yet comparatively modest influence of VIPVs on the overall magnitude of these excess demand events, when viewed on this scale.

As the previous analysis assumes a fixed 80% electrification rate, now we let the neighbourhood electrification rate vary and assess the ramifications on the frequency of demand surpassing transformer capacity, with and without VIPV. Excess demand moments (10-minute intervals) are quantified as a percentage of the total number of time intervals (including those without charge demand). The analysis also considers two VIPV configurations; roof, and roof and sides of the vehicle. This is shown in Figure 30 by the solid lines for three archetypal Netherlands neighbourhoods, urban, rural and semi-urban respectively.

Since any occurrence of excess demand can be detrimental for a grid operator and require some kind of solution, we will first look at the electrification rate where the problems start to appear. The simulations suggest that local grid issues arise at lower electrification rates in the semi-urban

[35] Note that the y-axis values are much smaller than in the previous plots. This is because the bins are also much larger (due to the larger span of the x-axis), This is simply a consequence of having a probability density.

context (approximately 20%), closely followed by the rural setting (approximately 30%), while the urban scenario exhibits comparatively fewer challenges until about 55% electrification. This correlates to rates of car ownership (0.4 cars per household, in contrast to 0.9 (rural) and 1.3 (semi-urban) cars per household in other neighbourhoods, as detailed in paragraph 1.3.1), resulting in fewer electric vehicles per household at the same electrification level. The difference is further compounded by lower transformer capacity per household (1.21 kVA/household in the semi-urban neighbourhood versus 3.52 kVA/household in the rural neighbourhood, as detailed in paragraph 1.3.1).

The threshold for the onset of excess demand events is similar for almost all EV scenarios (with and without PV). In fact, the scenarios with VIPV seem to indicate that VIPV may result in excess demand events at a lower electrification rate than without VIPV technology. This seems counterintuitive. Upon further analysis, we have found that this is due to a specific artifact of the chosen charging strategy. As the timing of charging and demand is based on the simulation of individual vehicles in the neighbourhood and the assumptions used for the charging behaviour, many of the vehicles in the simulation follow similar charge timings. In the case of the VIPV simulations, the lower electrification rate onset is due to a specific day in the winter where many VIPVs are plugged in during the same 10-minute interval when there is also a lot of non-BEV demand. In the no-VIPV case, this moment does not occur due to choices in the charging strategy in this particular set of simulations. It is particularly prominent in the urban case as there are fewer cars and fewer excess demand events overall. This event is essentially a combination of unfortunate coincidence and chosen charging strategy. This also illustrates the important conclusion that VIPV does not have a large impact in winter months. In a location like the Netherlands, when energy demand is heavier in the winter, VIPV technology does not significantly change the vehicle electrification level where onset of excess demand challenges would likely occur. Note that, as Figure 32 shows, this counterintuitive effect disappears when using charging strategy B.

There are two ways to address such issues: (1) scheduled smart charging to spread out the demand profiles; and (2) increase the local transformer capacity. The former solution is beyond the scope of this report. For the latter solution, another simulation is done assuming 25% increased local grid capacity. This can be seen in the dashed lines of Figure 30. As expected, increasing local transformer capacity increases the electrification rate at which the grid congestion issues occur but does not solve the problem entirely. But it also allows a clear comparison of the impact of VIPV as compared to grid capacity expansions at higher electrification rates. To better illustrate this, Figure 33 shows the total annual excess neighbourhood demand as a function of electrification rate. This is calculated by weighing each excess demand moment by the amount of excess energy required and summing over the full year. In the case of the semi-urban neighbourhood, with a larger number of EVs and a relatively small transformer capacity per household, the impact of VIPV at large electrification rates is seen to be on the order of (and even greater in the case of PV on roof and sides) a 25% increase in transformer capacity. This illustrates the situation if the transformer is undersized for the neighbourhood. In the case of an urban neighbourhood, the VIPV benefit is less pronounced but still improves the excess demand.

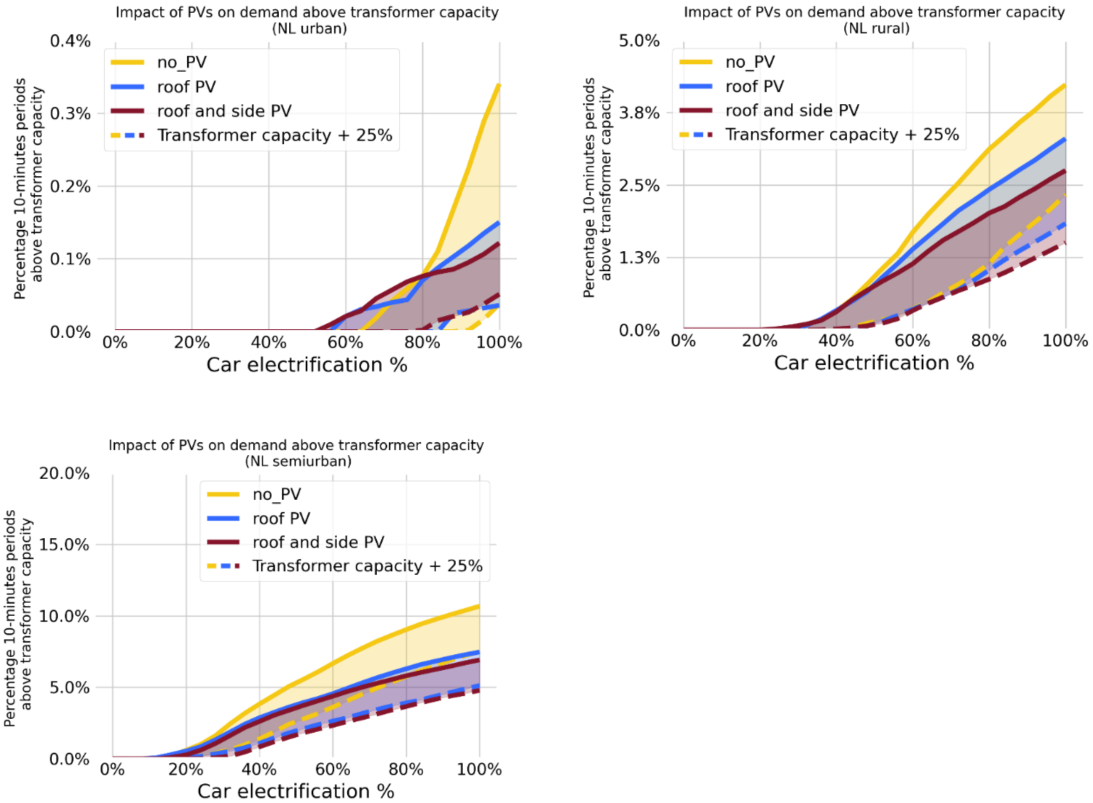


Figure 30: Percentage of time where the demand is above the transformer capacity as function of the neighbourhood vehicle electrification level for the neighbourhood in the Netherlands ((urban (top left), rural (top right), semiurban (bottom left))

As expected, most of the reduction in excess demand events due to VIPV in the Netherlands, occurs during the summer months, as shown in Figure 31. In fact, in the summer and spring, VIPV can offer an even larger impact than increasing the transformer capacity by 25%, as can be seen in Figure 31.

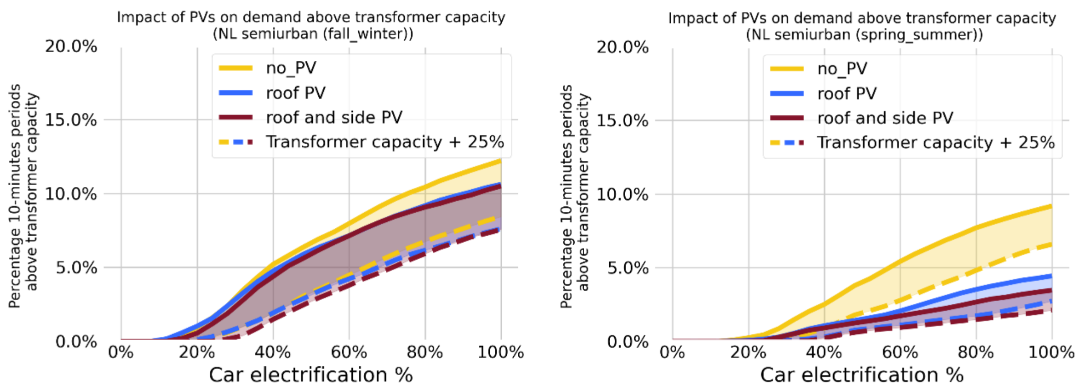


Figure 31: Seasonal comparison of the percentage of time where the demand is above the transformer capacity as function of the neighbourhood vehicle electrification level for the urban neighbourhood in the Netherlands, with fall-winter on the left and spring-summer on the right

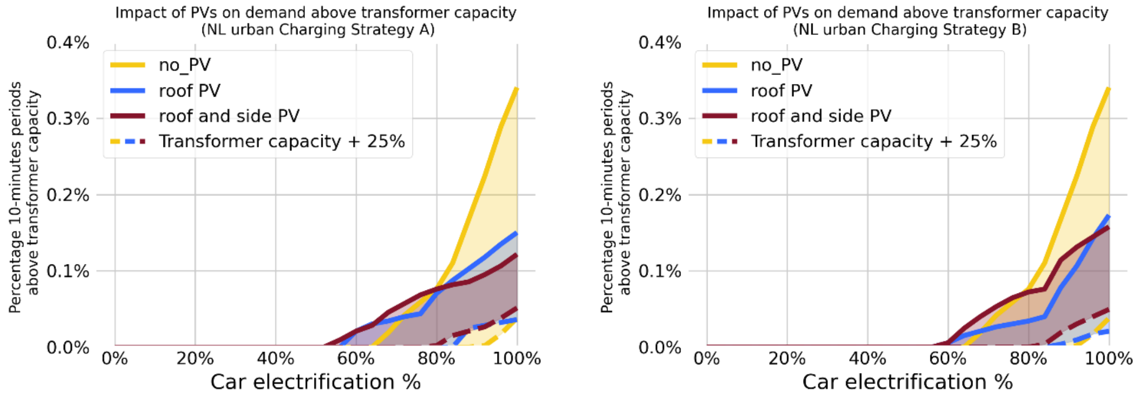


Figure 32: Yearly occurrences above transformer capacity, comparison between charging strategies A and B.

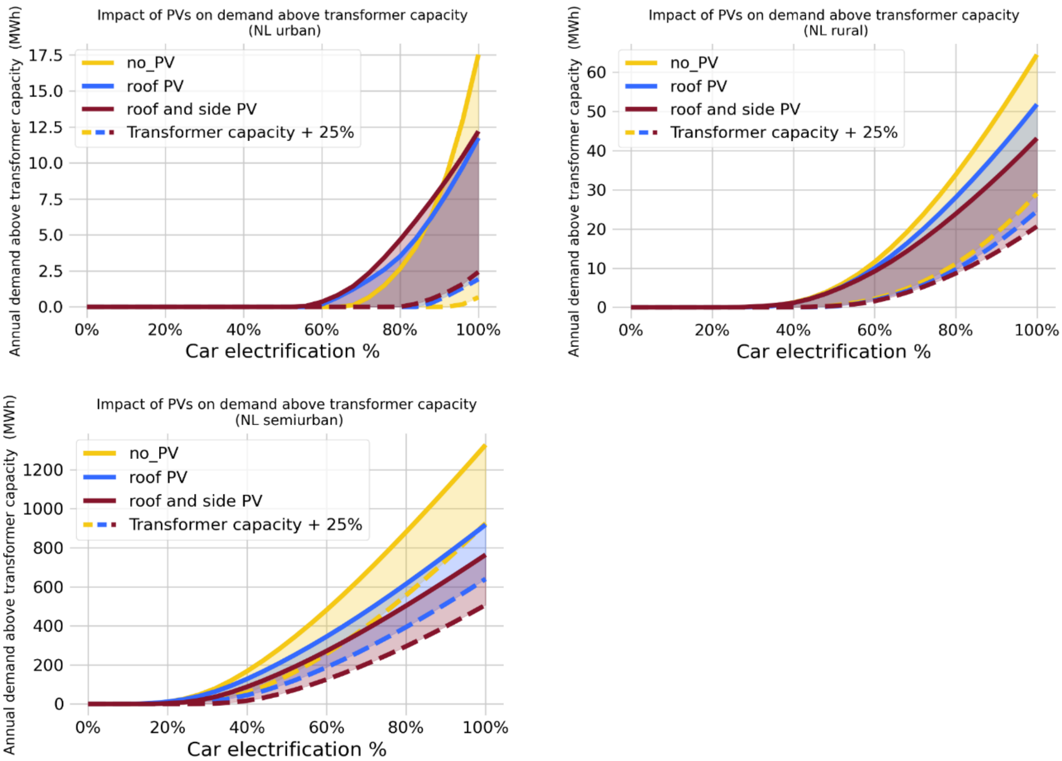


Figure 33: Annual demand above transformer capacity as a function of car electrification for the Dutch cases (urban (top left), rural (top right), semiurban (bottom left).

Section 1.5 translated the vehicle-level charging profiles into neighbourhood-level impacts, showing when and where BEV charging contributes to transformer-capacity exceedances and how VIPV can reduce the magnitude and frequency of excess-demand events (e.g. spring and summer).

Section 1.6 synthesises these results across vehicle, fleet, and grid levels, discusses key sensitivities and limitations, and draws conclusions on the role of VIPV in reducing grid congestion, charging demand, and infrastructure pressure during the transition to large-scale electrification.

1.6 Discussion and Conclusions

The theoretical analysis presented in this report reveals critical insights into the implementation and adoption of VIPV technology as a sustainable transport solution from the individual vehicle level to the broader fleet and the impact on grid congestion and infrastructure investment.

1.6.1. Vehicle Level

The analysis quantifies, at vehicle level, the fraction of annual energy demand that can be generated by VIPV. This varies significantly as a function of vehicle type, vehicle efficiency, location, and use. In a typical archetype of a medium vehicle driving peri-urban trips, the contribution of VIPV could be about 50% in southern Europe and 35% in central Europe. To the extremes, in Madrid, small passenger cars driving mostly on long highway trips, it is the lowest at around 23% per year while for shorter annual driving patterns (urban or occasional use) it can be as high as 60%-70%. In the case of an SUV with short annual driving distance (urban profile) and a large area for VIPV, the contribution can be as much as 81%. Simulations for vans estimate the contribution between 22% - 31% for all use cases in Madrid. For larger trucks used for goods transport over shorter distances or in the city, the contribution is between 10-15%, but only about 6% for long distance hauling. In the case of buses, we find it have the lowest contribution at < 10% mostly due to the high annual travel mileage leading as compared to the square meters of roof available for solar. In Amsterdam, due to the lower solar resource, the annual energy contribution is about 66% of that in Madrid for all archetypes except when limited by utilization of the solar energy.

Comparing VIPV with other measures to reduce EV energy consumption from the grid reveals that, for passenger cars with low annual mileage, VIPV can have an equal or larger potential than combined rolling resistance and air drag reduction measures, in both locations studied. Part of this is due to the avoidance of AC/DC charging losses when grid charging, giving a systematic efficiency gain when considering VIPV solutions.

For vehicles with a higher mileage, the balance changes. Where VIPV yield does (almost) not increase with higher annual mileage, the energy consumption reduction measures have an effect during every kilometre. For vans, but especially for trucks and buses, this means that the total potential of the other reduction measures is larger than the potential of PV.

The combined effect of PV and a set of viable energy consumption reduction options on the average electricity consumption per kilometre can be large with a remaining consumption below 50 Wh/km for some extreme cases of passenger cars and more than 20% for long-distance trucks.

1.6.2. Efficiency Measure Adoption Rate

In order for the efficiency measures analysed in this report to be adopted, VIPV or otherwise, they must be introduced by the vehicle manufacturers or desired by the fleet operators or first vehicle owners.

Adoption rate will be dependent on many factors including financial considerations, convenience, environmental benefits, or societal influences. Upfront additional purchase cost is likely a major determining factor. Assuming all of the measures can be added as an option, a first owner may choose a vehicle based on full write-off over their use period, which is set to 5 years for all vehicles in this study. This is indicative for private owners of passenger cars. Based on this assumption, current electricity prices, and estimated VIPV costs, VIPV is not financially attractive for any of the archetypes investigated in either location; the avoided electricity costs during the first five years do not currently not compensate the initial investment.

1.6.3. Total cost of ownership

Another approach is to look at total cost of ownership, which is a more common approach for commercial vehicles, as some of the upfront purchase costs will be reflected in the remaining residual value after 5 years. For vehicles manufactured after 2025 and 2030, an expected decrease in the costs of installed VIPV and an expected increase in its efficiency is also factored in. In general, VIPV does not significantly impact TCO, either a positively or negatively, irrespective of future timelines (2023, 2025 or 2030) or archetype. VIPV does become more attractive in the later years, but the effect is small relative to the total costs per km.

1.6.4. Fleet Level Impacts

A projection was made of the development of the EV fleet in the EU27 towards 2025 and 2030. If all EVs sold from 2024 onwards would be fitted with the selected efficiency options and VIPV, the consumption of almost 5,000 GWh could be avoided in the year 2025. In the year 2030, avoided energy demand is projected to be 27,000 GWh. Slightly more than half be attributed to VIPV. The large majority of the reduced electricity consumption comes to the account of passenger cars (80% in 2025, 70% in 2030). Urban and rural buses contribute the second largest impact on avoided energy demand, but almost entirely due to energy efficiency measures, not due to PV. This is due to the fact that non-VIPV energy efficiency measures will reduce grid energy demand for each kilometre driven contributing more to high mileage vehicles and use cases, while VIPV contribution is inherently limited on an annual basis. Translated into greenhouse gas emissions, the avoided grid electricity consumption would reduce the CO2-equivalent emissions in Europe by almost 1 Mton in 2025, and 3 Mton in 2030 (maximum; PV on top and sides). Average current and projected EU27 grid CO_2 emissions per kWh were used for this calculation.

A further objective was to estimate to which extent the fleet would grow faster as a result of improved TCO (and convenience) due to VIPV and efficiency options. However, the small positive or negative effect on TCO renders this exercise inconclusive without a clear methodology to value the convenience or placing a price on well-to-wheel CO_2 emissions from grid generated electricity.

1.6.5. Grid Impact

Finally, the impact of VIPV on grid congestion and capacity has also been studied based on the individual vehicle and fleet level results. One of the biggest concerns for the transition to an all-electric vehicle scenario is the impact on the grid, especially the local grid where many individuals and businesses would need access to charging infrastructure. This will require investments to ensure that energy demands can be met at the local level.

A neighbourhood grid level analysis shows that implementing VIPV on the electric vehicle fleet will likely also impact local grid congestions issues, particularly at high rates of vehicle electrification. At high rates of vehicle electrification with added VIPV technology, avoided grid energy can have a similar impact as increasing the local transformer capacity by as much as 25%. However, it does not seem to remove the risk of any one single excess demand events at any electrification level. To address this, staging of demand and smart charging will also be necessary. This staging can take place through various mechanisms, such as giving control to operators, having cars doing so themselves (with onboard software), or with a price incentive mechanism. VIPV would likely help in that situation as well, by alleviating issues and reducing the necessary staging effort, especially in some periods (such as spring and summer for the cases above).

Introducing VIPV also leads to a reduction in the number of annual charging moments for all vehicle archetypes. The amount of reduction can be quite extreme: almost no charging in the summer time for a small passenger car in an urban environment with very limited use. However, in most cases, the reduction in charging per year is more limited on the scale of 10%-15% on an annual basis with a high dependence on summer. When considering this combined with smart charging and strategies, this could directly result in a decreased need for individual charging locations as well.

1.6.6. Conclusions

The initial simulated results of VIPV and other vehicle energy efficiency measures, show promising convenience, infrastructure and environmental benefits for all vehicle archetypes. In particular, the ubiquitous adoption of VIPV technologies combined with local grid level energy demand measurement could potentially reduce expected infrastructure investments by as much as 20%-25%.

However, the widespread adoption of VIPV may be constrained by financial considerations. For passenger cars the return on investment at this time does not indicate that it would be widely adopted. However, for larger vehicles, total cost of ownership with VIPV does not change significantly. This suggests that for commercial uses other benefits, such as easier and more flexible logistics due to less dependence on base port charging and additional range could be stronger determinants for adoption. These types of benefits might also accelerate the electrification of this commercial transport.

This also suggests that policy incentives geared towards a comprehensive approach combining energy reduction measures and VIPV would have a large impact on adoption rates of fully electric transport.

The results presented here are based on a very narrow set of assumptions in order to ensure a meaningful analysis of the impact. However, in real life applications, many of the variables that have been simplified in this report will result in perhaps different conclusions. From field experience, based on company sales and test projects, the calculations here may not capture all of the possible benefits. Therefore, the irradiance measurement campaign as describe in Chapter 2 is very important in order to understand what solar resources are really available, how vehicles are really used, and how much, in practice the vehicle level assumptions here can be used to describe an scale to the fleet level. The SolarMoves consortium will continue to validate this set of simulations and analysis in order better understand and quantify the potential impact of VIPV.

2. Measurement, Pilot Testing methodology and Model validation

To ensure the accuracy and reliability of the simulations of Chapter 1 regarding on-board solar generation, it was essential to validate the model predictions with real-world measurements. The archetypes established in our previous analyses dictate the distribution of the three scenarios—urban, rural, and motorway usage—thereby influencing the predicted shading loss.

We have employed a shading model, to estimate shading loss based on vehicle archetypes and their respective operational environments. However, to enhance the credibility of our shading loss estimates, we conducted real measurements that correspond to various road types.

This validation process is described out in the paragraph 2.2 and 2.3, where the collected, empirical data is compared to the model's predictions. The insights gained from these measurements were instrumental in refining our model, leading to more accurate assessments of the potential energy contributions from on-board solar generation.

This chapter focuses on collecting real-world measurements of global horizontal irradiance using mobile sensors developed by Fraunhofer ISE, as well as energy measurements on vehicles from each partner.

2.1 On-Board Irradiance Measurements

This paragraph describes the methodology and implementation of real-world irradiance measurements on vehicles equipped with mobile sensor units. The one-year measurement campaign aimed to capture solar radiation data under actual operating conditions to validate model assumptions and assess the potential of vehicle-integrated photovoltaics (VIPV). The process includes sensor development, calibration, installation, and data acquisition protocols, as well as quality assurance measures to ensure reliable results. Additionally, the paragraph explains how vehicles were selected for testing, how archetypes were assigned, and how road type classification was integrated to improve correlation with modelled scenarios.

2.1.1. Real-life measurement of solar radiation on existing vehicles

Real-world measurements of solar radiation on vehicles were taken in a one-year measurement campaign. First the methodology will be explained from the construction, setup and installation of the mobile sensor units, the calibration, final test procedure and delivery to the partners. A short description of the data transfer method will be given, as well as the setup of the database and quality control schemes for the acquired measurement data. This part was extended during the campaign because the partner companies installing the sensors on their vehicle fleets or those of their partners found it very useful to have graphical user interfaces, for them and their customers, for their motivation and crosschecks of measurement and location data. External Grafana (graphical open-source software[36]) instances have been set up with an independent database for each of the partners.

[36] https://grafana.com/

During the measurement campaign, mounting information is being taken and entered into the systems logbook as well as taking photos and measuring the tilt angles, making it possible to apply data corrections in the evaluation phase when necessary.

Sensor development

The technical development of the mobile sensor unit is based on prior works for the publicly funded project in Germany called PV2Go[37]. The main board consists of a CPU with a 1 GB SD Card as a local storage device. It reads data from the signal amplification board and communicates with the telemetrics unit. This unit is derived from a standard industry device that is used in logging location data from professional vehicle fleets. The telemetrics unit is equipped with a SIM card holder, uses LTE Cat M1 technology and in areas where this network is not available, it has a 2G fall-back option. The satellite location technology GNSS is based on a combination of GPS and GLONASS and thus ensures a precise location and fast first fix (Cold 29s, Hot 1s, Position accuracy: 2.5m CEP50). This device has a 3D accelerometer integrated which we use for detecting if the vehicle on which the unit is mounted, is moving. In the moving case, we set the measurement resolution of the irradiance measurement to 1 s (configurable) and in the case of standing still, we average the measurement values to 5 min values and store these. This is an important part for the energy measurement as well as the very low power consumption of the telemetrics unit of <0,5mA in sleep mode. In between uses the device goes into sleep mode.

The measurement data is provided by a specially developed signal amplification board. This board allows for individual calibration according to the calibration values of the reference cell used for the measurement (see also Appendix G). This board is calibrated in such a way that for every sensor unit the same standard signal for the same measurement values is delivered which means that the actual sensor unit (the upper part of the unit) and the housing containing the data acquisition can be interchanged. The schematics of the electronics is shown in Figure 34 and a picture of the sensor board and battery is shown in Figure 34.

The main board also controls via charge controllers the status of the battery packs. These consist of three Lithium-Ion battery packs with 5200mAh rated capacity. This dimensioning was planned to guarantee at least two weeks of runtime in the dark because for this project we also want to evaluate the times when the vehicles are parked in areas without any sunlight.

[37] https://www.ise.fraunhofer.de/en/research-projects/pv2go.html; https://pv2go.org/
funded by „Bundesministerium für Wirtschaft und Klimaschutz (BMWK)“ under 03EE1015

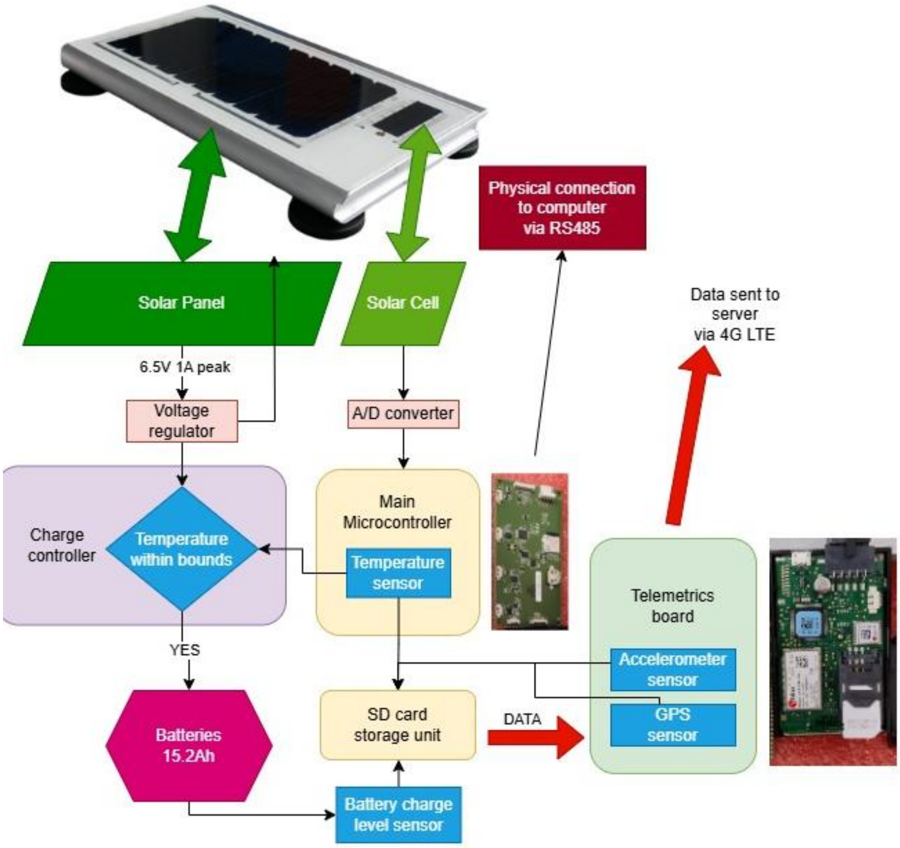


Figure 34: Schematics of sensor unit electronics

The actual sensor itself is produced in the module development department of Fraunhofer ISE. A reference cell and a solar module for the power supply have been laminated in one piece featuring the connection cables from the power supply and the sensor cables for irradiance and cell temperature. This laminated part is then being fixed waterproof in the aluminium housing (see Figure 36) and fitting with magnetic holders and a membrane valve for humidity control.

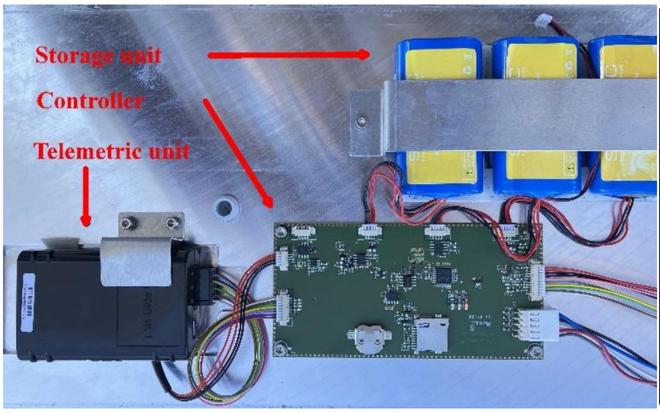


Figure 35: Picture of sensor unit electronics with battery packs

Figure 36: Picture of sensor unit

Because each and every part of a vehicle is regulated to ensure safety and as such has to be compliant with standards, it had to be assured that parts are approved, do not compromise the vehicle's integrity, and maintain accountability. To meet these regulations, the mounted sensor unit has undergone thorough testing in the DEKRA Automobil Test Center, Klettwitz, Germany[38]. The report is being referred to in the contract between the partners and Fraunhofer ISE for each unit in order to fulfil legal obligations.

2.1.2. Shortlist of vehicles and use cases for PV Integration testing

Application of archetype structure

At the start of the project a vehicle fleet to be deployed in the measurement campaign was suggested, based on the anticipated availability of vehicles from the SolarMoves partners. See Table 22. However, not all vehicles would be tested. Instead a shortlist would be defined for the integration testing. In this paragraph we will explain how the shortlist for the real world testing has been defined.

The ranking aspects for the shortlist have been defined as:

1. Potential for relative individual external vehicle efficiency improvements based on individual vehicle modelling.
2. Potential for absolute reduction in CO_2 emissions at fleet level based on the scenarios of Chapter 1
3. Ability to measure full energy demand and flow in the vehicle to validate full system models
4. VIPV system availability

In Paragraph 1.4.1, Figure 12 and Figure 13, we have shown the share of energy consumption by PV for each archetype, as resulted from the Energy Flow Model calculations. Based on that PV contribution it would be logical to choose the archetypes that have the highest PV contribution, which would result in the following list: *LP31, LP32, LP21, LP12. LP11 and LP10* (for the definition of these archetypes, see Table 3, in order of highest to lower PV contribution. However, these are all passenger cars. In order to have a larger spread over the vehicle types it would make more sense to use archetype per vehicle type that has the highest PV contribution per archetype. This results in the following list: *LP31, LV22, HB22 and HT11*.

[38] Prüfbericht 202049986-PV2GO in accordance with DIN 14620

Table 22: Vehicle fleet to be deployed in the measurement campaign

Vehicle Arche-type Code	Vehicle Class Type	Use Pattern	Available Vehicles	Usage	Companie	Solar Irradiance Vehicle (August 2023)	Available for VIPV Pilot (March 2024 or earlier)
LP11	Small Car	Daily urban commute	EV	personal use	Lightyear	1	yes
LP12		Daily peri-urban commute	EV	personal use	Lightyear	1	yes
LP13		Long distance highway travel	EV	personal use	Lightyear	1	yes
LP21	Medium Carr	Daily urban commute	EV	personal use	Lightyear	1	yes
LP22		Daily peri-urban commute	EV	personal use	Lightyear	1	yes
LP23		Long distance highway travel	EV	personal use	Lightyear	1	yes
LV11/LV 21	Light Commer cial Vehicle (van)	Local distribution	Electric Van	commercial deliveries	Sono/IM Efficiency	1	yes
			Electric Van			1	yes
LV12/LV 22		Regional distribution	Electric Van	refrigerator van/commercial deliveries	Sono/IM Efficiency	1	yes
			Electric Van			1	yes
HB11	Low-Floor Bus	Urban public transport service	Electric Bus	local transportation company	Sono	1-3	yes
HB12		peri-urban public transport service	Electric Bus	local transportation company	Sono	1-3	yes
HB22	High-Floor Coach	regional public transport	Diesel bus	intercity bus service	Sono	1-3	yes
HB23		long-distance highway travel	Diesel bus	intercity bus service	Sono	1-3	yes
HT11/H T12/HT 22	Trucks Rigid/Ar ticulate	urban or regional distribution	Diesel truck	commercial transport	IM Efficiency	2 (1x rigid, 1x articulated)	yes
HT23		long-haul freight transport	Diesel truck with trailer	commercial transport	IM Efficiency	2 (1x rigid, 1x articulated)	yes

The overall contribution to the CO_2 reduction is also important and depends on the number of vehicles per archetype in the European fleet. The scenario for the fleet development was reported in Paragraph 1.4.4 and Figure 24, gives the resulting distribution of the archetypes over the fleet as depicted. Combining this fleet consistence with the PV contribution gives the reduced energy consumption for the archetype fleet and was shown in Figure 26. From that graph it is found that the largest impact is achieved by the passenger car archetypes and especially the *LP22, LP23, LP32, and LP33* which are the medium sized and SUV passenger cars with a higher annual mileage. But again, it is more appropriate to spread the archetypes over the different vehicle types and in that case the LP33, LV21, HB12 and HT22 would be preferred. These four archetypes are different compared to the list that resulted from aspect 1, but, apart from LP33, they are the second best options in their vehicle type and it thus does not have a large impact on the result. For the choice between LP31 and LP33, the preference would be LP33 with the higher overall impact. *The shortlist would then be: LP33, LV21 or LV22, HB12 or HB22 and HT11 or HT22.*

Ad3 and Ad4: The lists derived above are the ideal lists with the vehicle archetypes that we would like to test in real world test conditions. All partners reached out to their contacts in order to have access to vehicles on which sensors could be mounted and/or that already have PV installed, and/or where we could have access to the energy consumption data of the vehicle. In the end several vehicles were found on which irradiance sensors were installed.

2.1.3. Installation

The list of available vehicles is shown below in Table 23. An overview of the sensors and their position on the different vehicles is given in Appendix H.

As these vehicles are in most cases used in logistics transport, we have no influence on the actual trips they make and as such the vehicles are no one to one match with the vehicle archetypes. However, based on the average trips of the vehicles we have assigned the archetype that matches best.

Table 23: Link of actual vehicles with mounted sensors and/or VIPV, and/or access to energy consumption and their match with the vehicle archetypes

Location	SolarMoves Archetype	Evaluated Archetypes	Access to Energy Consumption
IME, E-Volvo truck (top)	Rigid truck	['HT11' 'HT12']	Yes
IME, E-Volvo truck (right side to the driver)	Rigid truck	['HT11' 'HT12']	Yes
IME, E-Volvo truck (left side to the driver)	Rigid truck	['HT11' 'HT12']	Yes
IME, Peugot Boxer Luton (Van Obelix) (right)	Large van	['LV21' 'LV22']	No
IME, Peugot Boxer Luton (Van Obelix) (top)	Large van	['LV21' 'LV22']	No
IME, Peugot Boxer Luton (Van Obelix) (left)	Large van	['LV21']	No
IME, Renault Clio Bonnie (top)	Small passenger car	['LP12' 'LP10' 'LP13' 'LP11' 'LP14']	No
IME, Renault Clio Clyde (top)	Small passenger car	['LP11' 'LP12' ' LP14' 'LP10']	No
IME, DAF truck-trailer 1 (top)	Tractor-trailer	['HT22' 'HT23']	No
IME, DAF truck-trailer 2 (top)	Tractor-trailer	['HT22' 'HT23']	No
IME, DAF truck-trailer 3 (top)	Tractor-trailer	['HT22']	No
IME, DAF truck side (97-BLS-9) (top)	Rigid truck	['HT12' 'HT11']	No
IME, DAF truck side (98-BLJ-4) (top)	Rigid truck	['HT11']	No
IME, DAF truck side (97-BLS-9) (right top)	Rigid truck	['HT11' 'HT12']	No
IME, DAF truck side (97-BLS-9) (left bottom)	Rigid truck	['HT11']	No
IME, DAF truck side (97-BLJ-4) (top)	Rigid truck	['HT12' 'HT11']	No
IME, Scania truck		['HT12' 'HT11']	No
IME, Hitachi Truck (Europe) 1	Rigid truck	['HT12']	No
IME, Hitachi Truck (Europe) 2	Rigid truck	['HT12' 'HT11']	No
IME, Hitachi Truck (Europe) 3	Rigid truck	['HT12']	No

Location	SolarMoves Archetype	Evaluated Archetypes	Access to Energy Consumption
Lightyear Layer, Lightyear 0	Medium sized pass. car	['LP22' 'LP21']	Yes
Lightyear Layer, VW crafter (roof facing side)	Large van	['LV22' 'LV21']	No
Lightyear Layer, VW crafter (roof facing sky)	Large van	['LV21']	No
Lightyear Layer, Tesla Model 3	Medium sized pass. car	['LP21' 'LP22']	No
Lightyear Layer, Spain	Medium sized pass. car	['LP22' 'LP21']	No
Lightyear Layer, Italy	Medium sized pass. car	['LP21' 'LP22']	No
Sono Motors GmbH, Munich medium car	Low-floor bus	['LP22' 'LP21']	No
Sono Motors GmbH, Nitra Slovakia 1	Low-floor bus	['HB11' 'HB12']	No
Sono Motors GmbH, Zilina Slovakia 2	Low-floor bus	['HB11' 'HB12']	No
Sono Motors GmbH, Nitra Slovakia 2	Low-floor bus	['HB11' 'HB12']	No
Sono Motors GmbH, Essen low floor bus 1	Low-floor bus	['HB11' 'HB12']	No
Sono Motors GmbH, Topolcany Slovakia	Low-floor bus	['HB12']	No
Sono Motors GmbH, Essen low floor bus 2	Low-floor bus	['HB11' 'HB12']	No
Sono Motors GmbH, Hof low floor bus	Low-floor bus	['HB11']	No
Sono Motors GmbH, Local Van	Large van	['LV21' 'LV22']	No
Sono Motors GmbH, Munich bus	Low-floor bus	['HB11']	No
Sono Motors GmbH, Coach Bus	High-floor coach	['HB22']	No

2.1.4. Data Quality assurance

The integrity and reliability of data is important for accurate evaluations and analysis. To ensure high standards of data quality, a comprehensive data quality control process is implemented, which encompasses several critical steps. For details on these steps see Appendix I.

2.1.5. Measurement data evaluation

The analysis focuses on several key metrics related to total horizontal solar irradiance. The momentary irradiance value and cell temperature are recorded in an interval that can be defined individually, here we use secondly values and are averaging them to 5 min values in stopped state. Furthermore, the average daily and yearly energy sum of irradiance are calculated (and/or interpolated). Additionally, both the minimum and maximum positions of the data are documented.

The average speed while moving is calculated to assess performance during movement. Data availability is also recorded, indicating the percentage or extent of available data for analysis.

As an example, the graph below shows an overview of the timespan of available data for each installed sensor. This visualization highlights the duration for which data has been collected, for each sensor in the dataset.

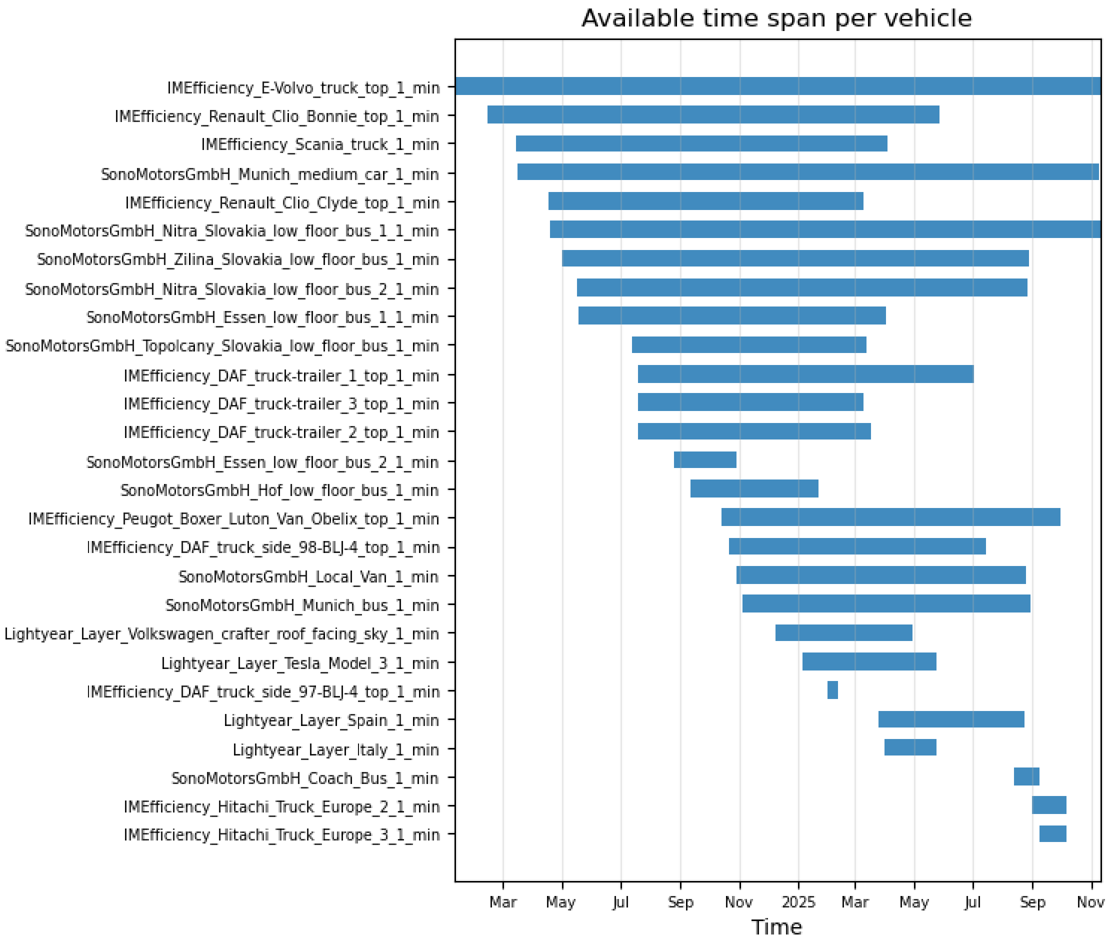


Figure 37: Data availability for selected sensors

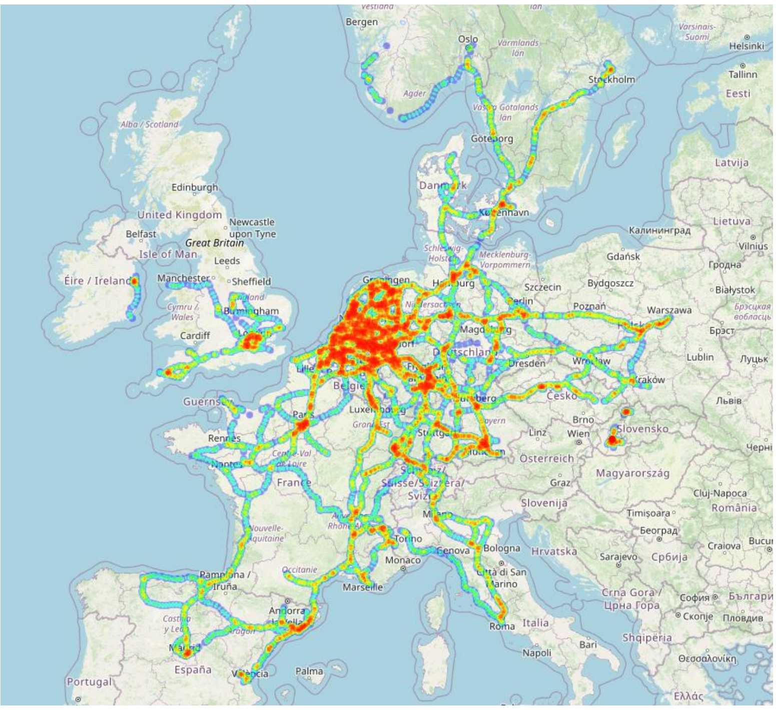


Figure 38: Heatmap of covered distances in Europe

Since the beginning of the project until 10.11.2025 in total 1.294.626 km have been travelled by vehicles with mounted mobile sensors of which 861.059 kms have been driven by IM Efficiency partner vehicles, 411.068 kms by Sono Motors partner vehicles and 22.498 kms by Lightyear vehicles, coving the total area as shown in Figure 38. The scale ranges from blue, few datapoints, to red, many datapoints. As can be seen, data has been collected all over Europe, with a focus on Belgium and the Netherlands.

2.1.6. Assigning archetypes to available vehicles

The initial definition of the vehicles archetype has been assigned by the partners to the closest fit from the SolarMoves archetypal system. However, a vehicle will never have an exact fit with the archetypal description. For this reason, later in the evaluation process, the type of road used has been assigned to every time step of the data. This allowed us to be able to assign different archetypes to the same vehicle according to its use of the road type. In this way the measurement data correlate much better to the original archetypal definition.

For assigning the road use type at each time step of the data, we chose to use the *Local Climate Zone*[39] world wide data base. The system defines ten zones in built areas from high-rise through midrise to low-rise buildings with different densities, sparse built, heavy industry and seven types of land uses (see Figure 39).

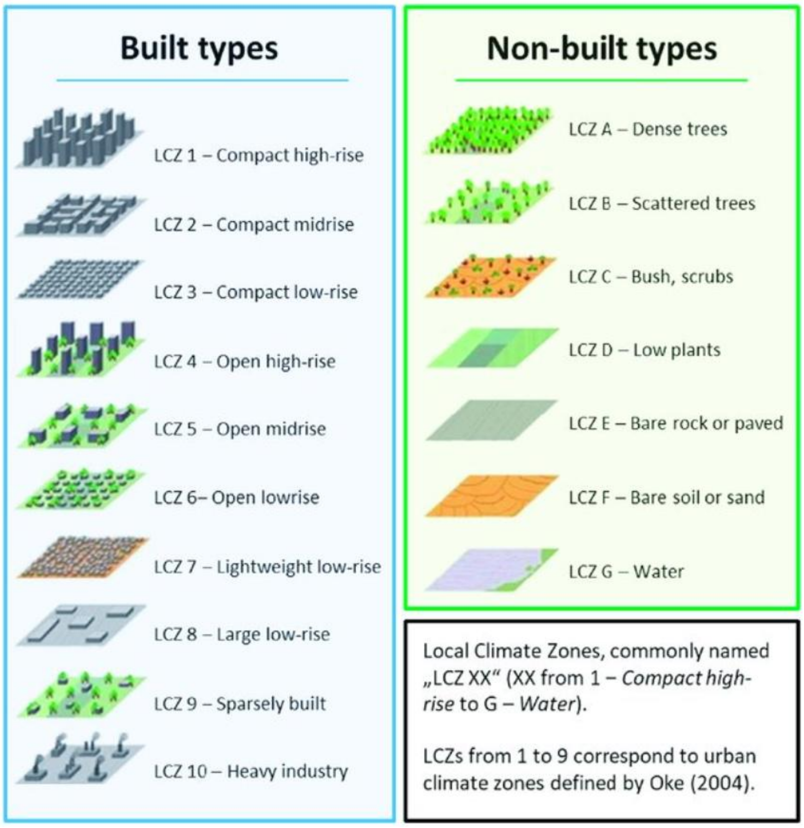


Figure 39: Zoning methodology according to Local Climate Zones (LCZs) as a generic, culturally-neutral description of land-use and land-cover[40]

[39] https://www.wudapt.org/lcz-maps/
[40] Based on Stewart & Oke, 2012; Oke, 2004

For visualization purposes, the area around Eindhoven with the LCZ typology is shown in Figure 40 with an overlay of open street map database to show how the LCZs are visible in the infrastructure of a town.

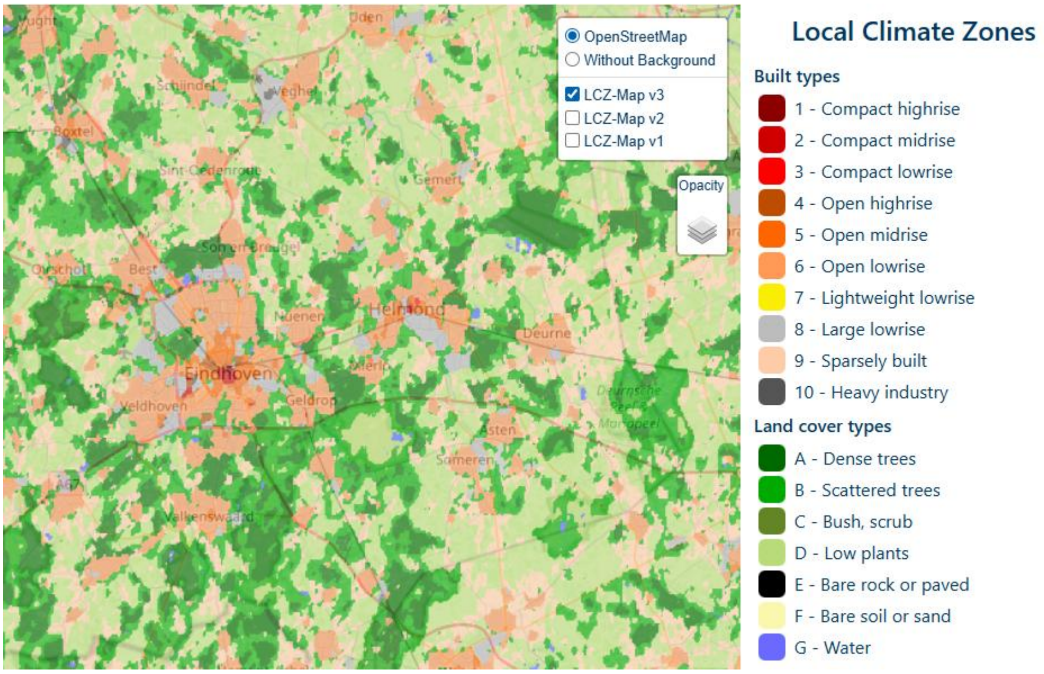


Figure 40: Overlay of local climate zones with open street map for Eindhoven area

Now for approximation with the road type percentages of the original archetype definitions (Table 1), the evaluation procedure includes the zoning of all driven routes according to the LCZ database. This creates the possibility of determine the shading factor according to archetype and road usage.

For our evaluations, we have used the following system: [41] The LCZones [1, 2, 3, 4, 5, 7, 8, 10, 15] are used for classification as **urban** and [6, 9, 11, 12, 13, 14, 16, 17] as **semiurban** (see Figure 39 for the LCZ definitions) . When speed is found to be higher than 70 km/h, the classification for road type is **motorway**.

In section 2.1, the on-board irradiance measurement campaign was described. It has produced a large, quality-controlled dataset covering different vehicle types, use patterns, road environments, and climatic conditions across Europe. Section 2.2 uses these real-world measurements to validate the irradiance and shading assumptions applied in Chapter 1 by comparing vehicle-measured irradiance with satellite-derived estimates and other reference inputs under both driving and parking conditions.

2.2 Irradiance model validation

This paragraph validates the irradiance modelling approach by comparing satellite-derived solar irradiance with ground-based meteorological measurements and real-world data from vehicle-mounted sensors. The analysis assesses the accuracy of the Heliosat method, quantifies deviations, and examines the influence of shading on VIPV performance under diverse conditions. By introducing metrics such as irradiance factor and energy-weighted shading factor, the study

[41] https://essd.copernicus.org/articles/14/3835/2022/

evaluates how well the modelled assumptions align with actual measurements across different road types, seasons, and operational states. These insights are critical for refining shading models and improving predictions of VIPV energy yield.

2.2.1. Satellite irradiance versus meteorological irradiance

The purpose of this analysis was to illustrate the performance of satellite-derived irradiance at meteorological sites without shading, supporting the interpretation of the comparisons to measurements on the roads. Data from Deutscher Wetterdienst (DWD)[42] meteorological stations measuring ground-based solar irradiation for the years 2022 and 2023 was used. The weather data are recorded at 10-minute intervals from 18 weather stations distributed across Germany. Measurements include the Global Horizontal Irradiance (GHI) and the local temperature.

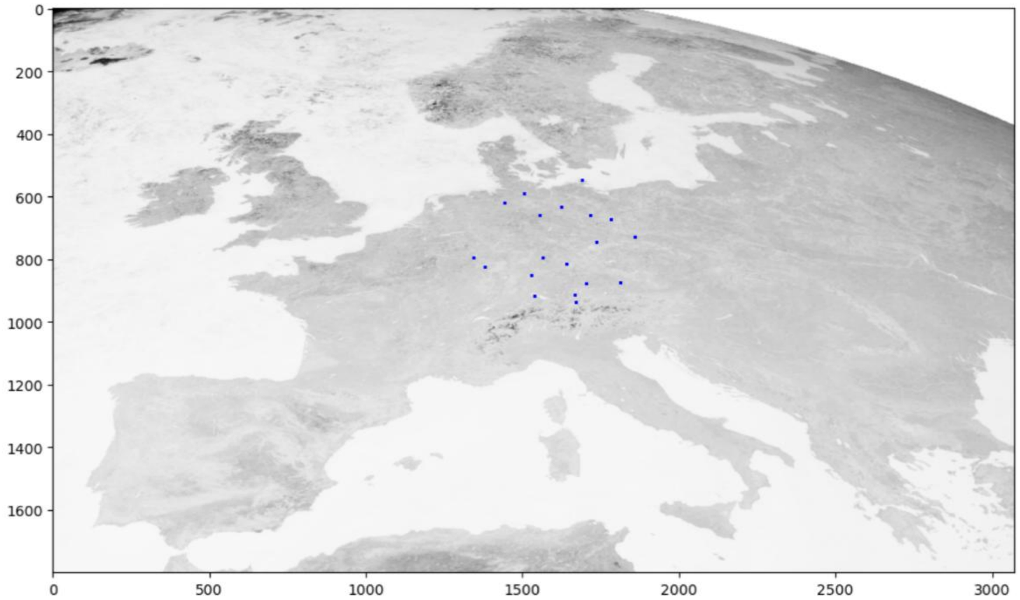


Figure 41: Meteosat Second Generation satellite imagery from High Resolution Visible (HRV) channel of Europe region, pre-processed to remove clouds, with the blue dots displaying the location of the 18 DWD weather stations in Germany

To assess the viability of using the Heliosat approach, an analysis comparing Heliosat derived irradiance values against the measured GHI values at the weather stations was performed. To perform this analysis the weather data measurements were resampled to a 15-minute resolution to match the frequency of the satellite imagery used in the Heliosat method.

A comparison of ~ 600,000 measurements in 2022 and 2023 of ground solar irradiance from DWD across the 18 weather stations is plotted on the scatter plot below. In addition a relative root mean squared error (RRMSE) and a relative bias was calculated to understand the correlation between the measured and Heliosat derived irradiances. The RRMSE and relative bias were calculated as follow,

[42] Deutscher Wetterdienst. (n.d.). Retrieved from https://www.dwd.de/EN/Home/home_node.html

$$RRMSE = \left(\frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(GHI\_M_i - GHI\_P_i)^2}}{\frac{1}{n}\sum_{i=1}^{n} GHI\_M_i} \right), \text{and } RelativeBias = \frac{\sum_{i=1}^{n}(GHI\_M_i - GHI\_P_i)}{\frac{1}{n}\sum_{i=1}^{n} GHI\_M_i}$$

where, n is the number of observations or data points in the dataset, GHI_Mi are the GHI values measured from the vehicle sensor for the i^{th} observation, GHI_Pi are the predicted values of the GHI dependent variable for the i^{th} observation.

Applying these equations to the data from 2022 and 2023 yields an RRMSE of 0.22 and a relative bias of 0.0 as shown in Figure 42. This comparison of Heliosat derived irradiance to the measured GHI shows on average a deviation of 22%. This deviation is reasonable given the complexity of the solar irradiance derivation task, and the many variables involved (cloud cover, time of day, atmospheric conditions etc.) These results are consistent with the performance of the method described in the literature[43]. The relative bias of 0.0 indicates that the approach does not systematically overestimate or underestimate the solar irradiance, and the errors are randomly distributed indicating that the Heliosat approach is well-calibrated.

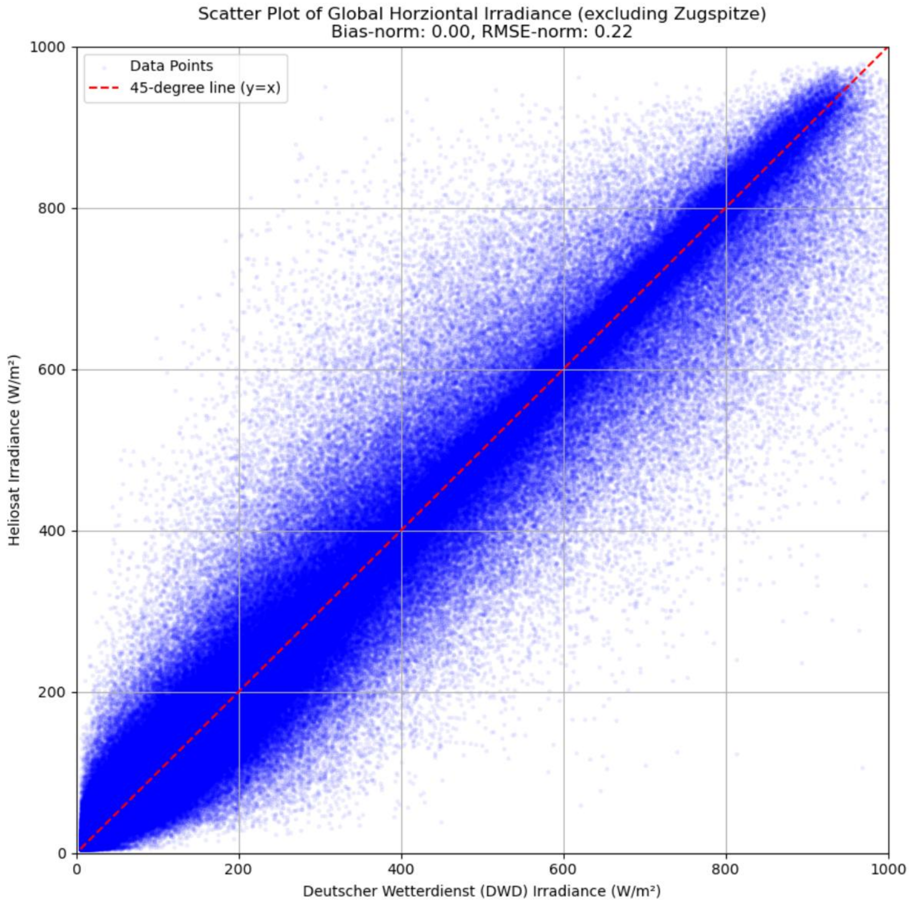


Figure 42: Scatter plot of Heliosat satellite irradiance against measured irradiance from Deutscher Wetterdienst (DWD)

[43] Lorenz, E. & Betcke, Jethro & Drews, A. & de Keizer, Corry & Stettler, S. & Scheider, M. & Bofinger, Stefan & Heinemann, Detlev. (2007). Intelligent Performance Check of PV System Operation Based on Satellite Data (PVSAT-2), Final Technical Report.

2.2.2. Satellite irradiance versus measured vehicle irradiance

In this study, the Heliosat method for calculating solar irradiance was applied and compared to the data acquired from vehicle-mounted sensors. This allowed us to dynamically compare the satellite-derived irradiance with data gathered from sensors exposed to a variety of geographical and atmospheric conditions. Importantly, it also offers an opportunity to assess the impact of shading on the vehicle-mounted sensors.

The steps taken to perform this analysis were first to acquire and clean the datasets, then to convert from the geographic coordinate system used by the GPS to a coordinate system representing the relevant pixels in the satellite image, then to run the Heliosat algorithm, and finally to analyse the results.

Measurements

The satellite analysis was performed on sensors mounted on vehicles of three companies, see the table below. The sensor can be mounted in different orientations, on the top or the sides of the vehicle, and the data includes both measurements from moving vehicles and stationery.

Table 24: Datasets in which satellite irradiance were derived, including the date range currently processed with satellite imagery, the number of sensors and the total number of data points

Dataset	Start Date	End Date	# of Sensors	# of Datapoints
IM Efficiency	2024-02-14	2024-11-10	9	938,164
Lightyear Layer	2024-05-01	2024-12-10	3	412,530
Sono Motors GmbH	2024-03-17	2025-01-21	9	2,552,972

From these datasets the pertinent fields are longitude, latitude, and the irradiance measured on the sensor, the table below gives a complete description of the data fields in the analysis.

Table 25: Variables in the acquired datasets from vehicle mounted sensors

Field	Description
Time	The exact date and time of the measurement, at a 1 second resolution.
Latitude and Longitude	The geographic coordinates of the vehicle at the time of measurement.
Irradiance	The solar irradiance measured by the vehicle-mounted sensor (W/m^2).
Speed_in_kmh	The speed of the vehicle when the measurement was taken (km/h).
Sensor_ID	Identifier for the specific sensor that took the measurements.
Sensor_name	The name describing the sensor that took the measurement.
Irradiance_mean	The moving average of irradiance, averaged 60 seconds before the timestamp (W/m^2).

Georeferencing to Satellite Image Coordinates

To these vehicle sensor data, a translation is applied to convert from the longitude / latitude pair of the GPS to the satellite coordinate system defined as the line offset / Col offset. In addition, since the satellite imagery is acquired with a 15 minute frequency, and the GPS data received every second, the two closest corresponding images are looked up.

The spatial transformation is demonstrated in the below figure, showing a trajectory over two hours of a single sensor. The figure illustrates how the map translates to our satellite imagery coordinate system and highlights the resolution in the satellite imagery. Note that this trajectory would span multiple satellite images, since it is over a two-hour period, here for simplicity we show the trajectory on one image to demonstrate the spatial scaling.

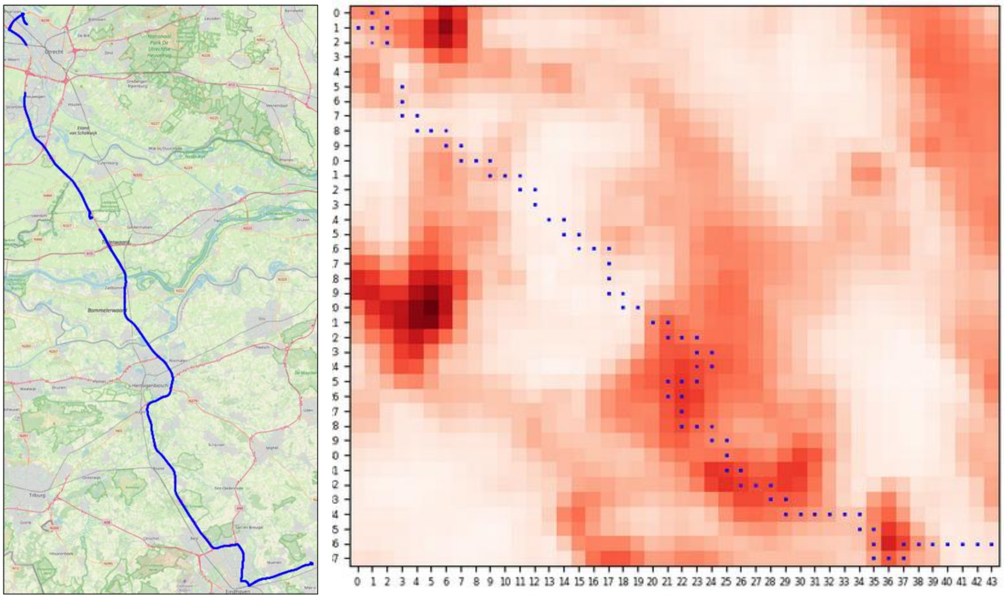


Figure 43: Single vehicle trajectory in the Utrecht region of the Netherlands from 2024-04-18 until 2024-04-18. Left: trajectory with GPS coordinates plotted on OpenStreetMap, Right: trajectory plotted on satellite image with resolution of 1 pixel approximately as 1 km^2

Run Heliosat processing for coordinates / images

The Heliosat algorithm is run for each location in the dataset and the irradiance calculated using the nearest satellite image recorded, The method produces three additional fields including the field of interest the global horizontal irradiance.

Table 26: Variables added to datasets after running Heliosat satellite irradiance algorithm

Field	Description
Global	Total solar radiation received at a specific location, including both direct and diffuse components (W/m^2).
Diffuse	Solar radiation that has been scattered by molecules and particles in the atmosphere, reaching the surface from all directions. (W/m^2).
Clearsky	Solar radiation conditions under a clear sky, where direct sunlight is unobstructed by clouds, representing maximum solar radiation potential (W/m^2).

Example for IM Efficiency data

Each vehicle dataset from the three companies IM Efficiency, Lightyear Layer, and Sono Motors GmbH were analysed separately. Initial quality checks were performed, plotting all trajectories on a map to check if the data are within the expected geographical regions. Additionally for each sensor in the dataset a selection of daily profiles were plotted to get intuition about the irradiance profiles. Examples of these daily irradiance profiles for a single sensor PV2085 in the IM Efficiency dataset can be seen in the figure below and shows the satellite irradiance in different conditions: partly clouded, sunny and clouded. In general, the satellite irradiance is higher than the irradiance on the sensor showing significant effects of shading on the sensors.

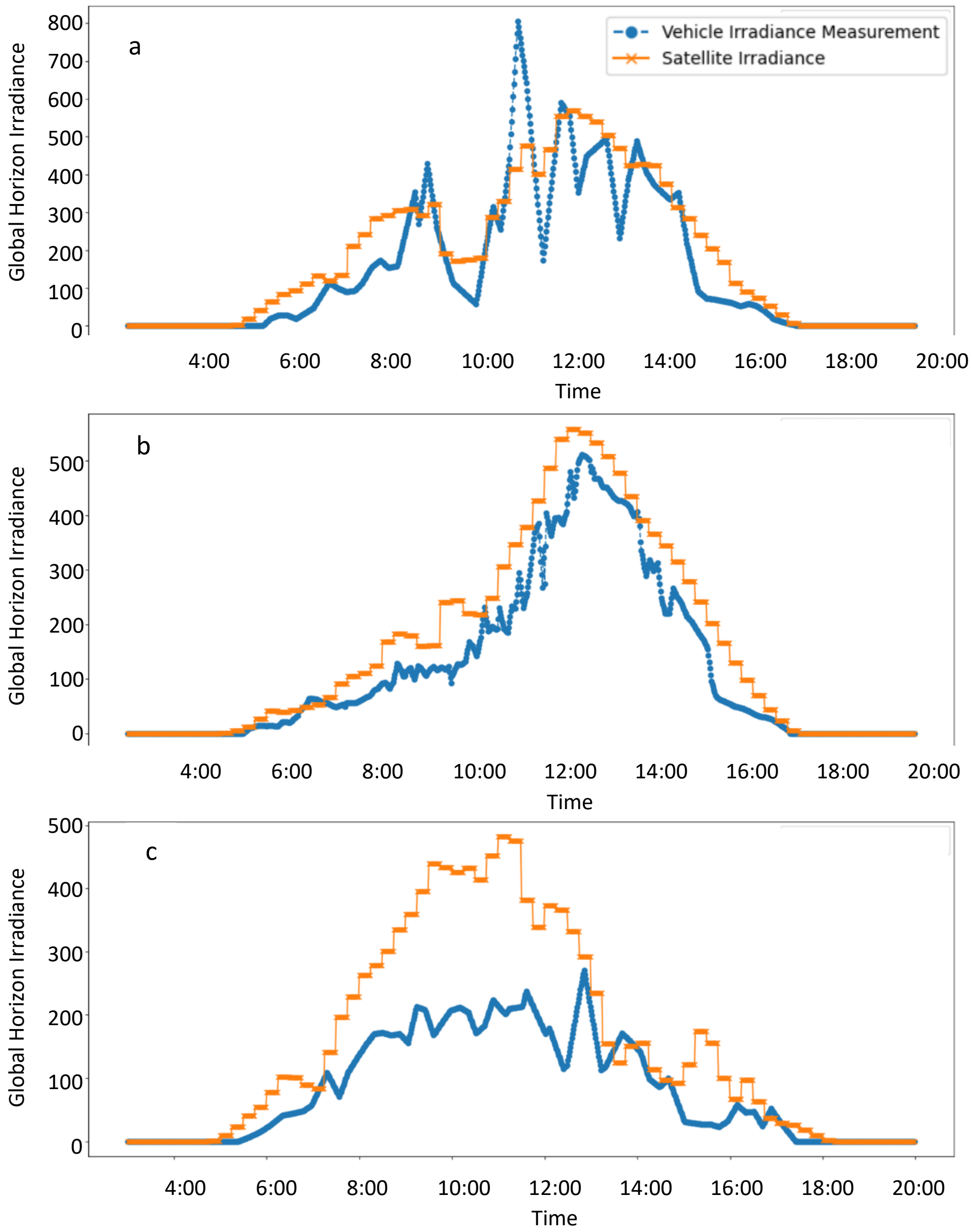


Figure 44: Satellite irradiance and measured vehicle irradiance profiles from thee IM Efficiency dataset, on three different randomly selected days: (a) on 2024-09-23, (b) 2024-09-18, and (c) 2024-06-06

This was checked further for each top mounted sensor in the data set with sufficient data, by making a scatter plot of the measured GHI against the Heliosat derived GHI. For the IM Efficiency data, the scatter plots are shown below.

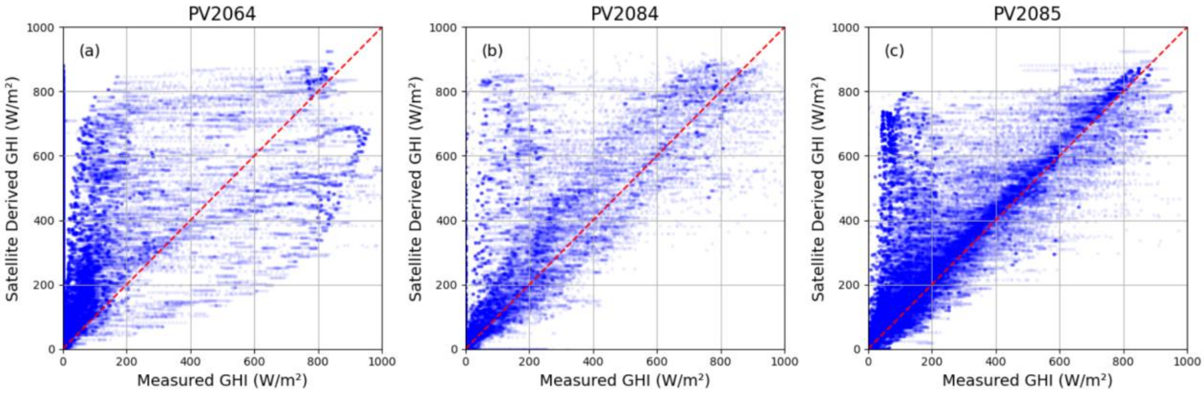


Figure 45: Scatter plots for each top mounted sensor in the IM Efficiency dataset showing the relationship between the Heliosat satellite derived irradiance and the measured vehicle irradiance. (a) IM Efficiency Renault Clio Clyde, (b) IM Efficiency E-Volvo truck, and (c) IM Efficiency Peugeot Boxer Luton Van Obelix

In the analysis of sensor data, the RRMSE and relative bias scores are higher than those observed in the previous analysis of weather stations. This increase in error can be attributed to several factors, primarily the propagation of positional inaccuracies resulting from the resolution of satellite imagery and the down sampling of high-frequency GPS measurements to 15-minute intervals. High-frequency GPS data, collected at 1-second intervals, captures rapid movements and positional changes with great precision. However, when this data is down sampled to longer intervals, critical information can be lost, leading to the averaging of movements and potentially missing quick directional changes. This loss of detail significantly contributes to the estimation errors in the vehicle's position and trajectory.

In addition to these randomly distributed error sources, it is the above plots show in general datapoints on or above the red line, indicating higher satellite irradiance compared to the truck irradiance which shows the losses in irradiance due to shading effects.

2.2.3. Irradiance factor, energy weighted shading factor and shading factor

In Chapter 1, we reported on the modelling of the irradiance as input for the Energy Flow Model (EFM). The model uses the global horizontal irradiance at the location of the vehicle as obtained from the Meteonorm or satellite dataset. To account for shading losses by nearby objects like buildings, a generic seasonal irradiance model is used for each road type: ‘Urban Road’, ‘Semi-Urban Road’, and ‘Motorway’ (Figure 8).

To validate the model, as a first step, the irradiance factor is calculated as the ratio between the measured irradiance on the vehicle and the global horizontal irradiance[44] predicted by the satellite model. This ratio indicates how much of the total available radiation is available on the vehicle.

[44] Performance analysis of solar cars for everyday use — Eindhoven University of Technology research portal (tue.nl)

$$Irradiance\ Factor\ (IrF)\ =\ \frac{measured\ irradiance\ (Gmeas)}{satellite\ (Gsat)\ or\ meteo\ irradiance(Gmeteo)}$$

An overview of the Heliosat methodology for deriving the satellite irradiance is described in paragraph 2.1.1 and Appendix J.

The shading factor can then be derived by:

$$Shading\ Factor\ (SF)\ = 1 -\ \ Irradiance\ Factor\ (IrF)$$

When determining the effect of shading on the VIPV yield, we also look at the energy loss due to shading instead of looking purely at the loss in irradiance. The reason is that in the morning and evening, the absolute energy loss due to a certain shading situation is less than during noon. In the following we use these definitions:

- G(sat)=satellite-derived GHI
- G(cls)=clear sky GHI
- G(meas)= on vehicle measured GHI

The relation G(sat)/G(cls) will be called *Clear Sky Index*. This ratio indicates how sunny it is, with 1 being very sunny and 0.5 being partly clouded. G(meas)/G(sat) gives the portion of irradiance power density available on the vehicle (even in the presence of clouds, as the satellite data will include the reduced irradiance due to clouds). This relation will be called irradiance factor IrF and will be used in the second part of the evaluation of all data referring to the simulated scenarios from Chapter 1.

The **E**nergy weighted **S**hading **F**actor **ESF** will be defined here as the complement of the relation G(meas) / G(sat) summed up for the time range chosen:

$$ESF\ =\ 1 - \sum_t \mathrm{G\ (meas)} * \ \Delta \mathrm{t}\ /\ \sum_t \mathrm{G\ (sat)} * \ \Delta \mathrm{t} \qquad (1)$$

When no clouds, no surface shading and no systematic bias are present, ESF is (close to) 0 and when we measure e.g. 80% of the available irradiance over the time observed, the ESF is 20%.

After data cleaning, we apply the following conditions to all data evaluations to define a daylight period for analysis:

- sun elevation >= 10°
- measured irradiance >= 1W/m^2

In the paragraph below a validation of the methodology is given by comparing satellite and meteorological irradiance to measured irradiance. Finally the methodology is applied to vehicle mounted sensors and results are evaluated.

2.2.4. Shading factor case studies

In this paragraph we will first zoom in on a few case studies to show the effect of parking. As the majority of the vehicles are ICE vehicles, and the drivers did not get instruction for parking in the sun, as would be logical for a VIPV vehicle, parking in the shade can have a substantial influence on the data.

Case study 1: Volvo truck

The Volvo truck contains 3 sensors, one at the top and 2 on each side. The dataset used for the model validation uses one-minute instantaneous values as well as 1 minute mean values.

From the dataset, three days were selected to compare the truck irradiance with meteorological data from KNMI and satellite irradiance data, namely July 9, 12 and 30, which correspond to partly clouded, clouded and clear sky days respectively. Figure 48 shows the measured irradiance on the truck as well as the KNMI data of the nearest meteo station and GHI satellite data. Clearly the satellite data show higher irradiances in the morning and afternoon on the clouded and partly clouded days. The KNMI data seem to match better. On the clouded and partly clouded day the irradiance fluctuates strongly due to passing clouds. As the KNMI sensor and the satellite data area always a bit off from the actual location, it makes it impossible to directly compare the track data with those irradiance data sets as passing clouds will pass at a different time. A daily average would make more sense. When looking at the sunny day (Figure 48), the truck irradiance is higher than the KNMI irradiance.

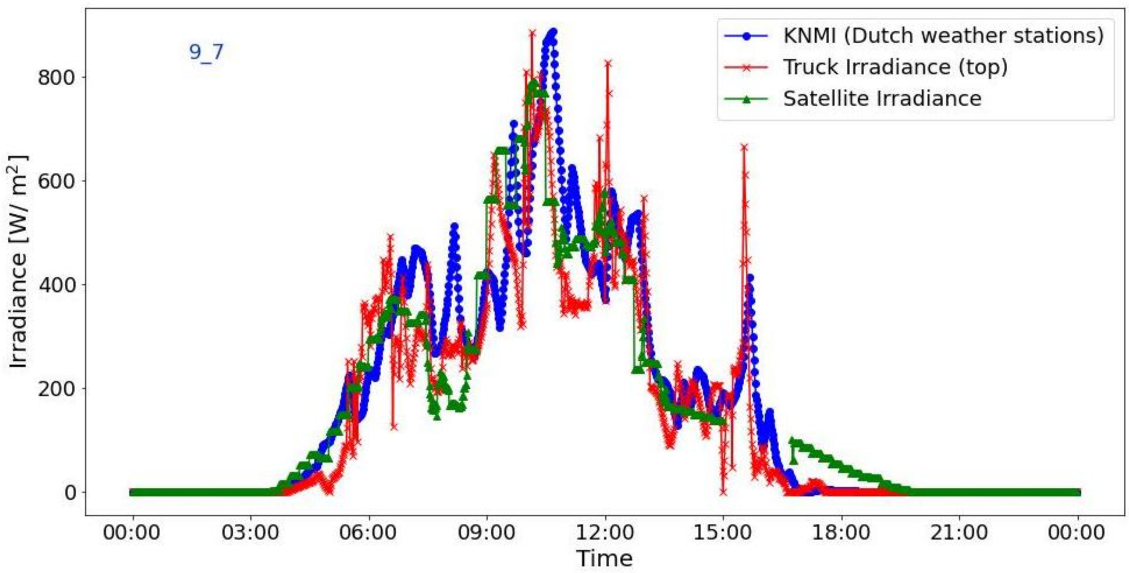


Figure 46: July 30: KNMI, Truck and satellite data on a partly clouded day

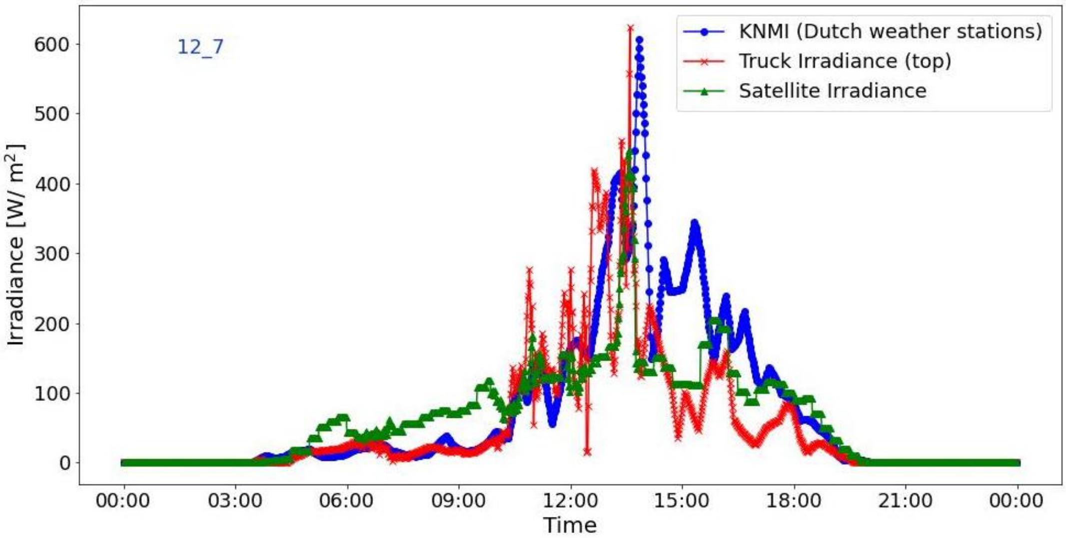


Figure 47: July 30: KNMI, Truck and satellite data on a clouded day

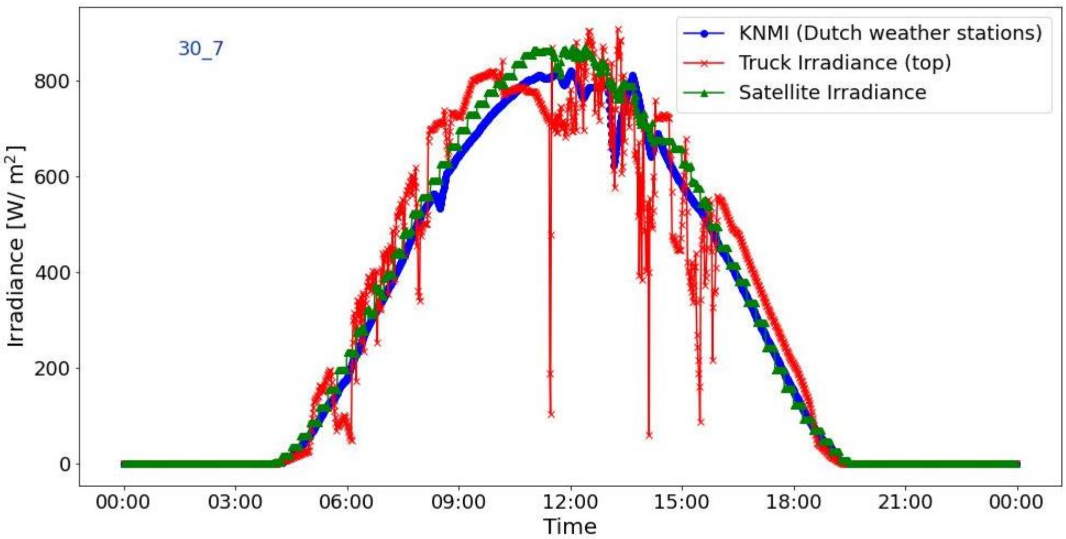


Figure 48: July 30: KNMI, Truck and satellite data on a sunny day

There could be some extra reflection from nearby objects or from the spoiler of the truck itself. Another reason for the higher irradiance could be the fact that the sensor on top of the truck is not mounted perfectly horizontal. We corrected the truck data to compensate for the tilt, but this might still cause some differences.

As a start for the irradiance model validation, all irradiance data from July 5 up to August 6 was used. The truck location for this timeframe is given in Figure 49. Figure 50 gives the distribution of the different terrain types for the truck locations.

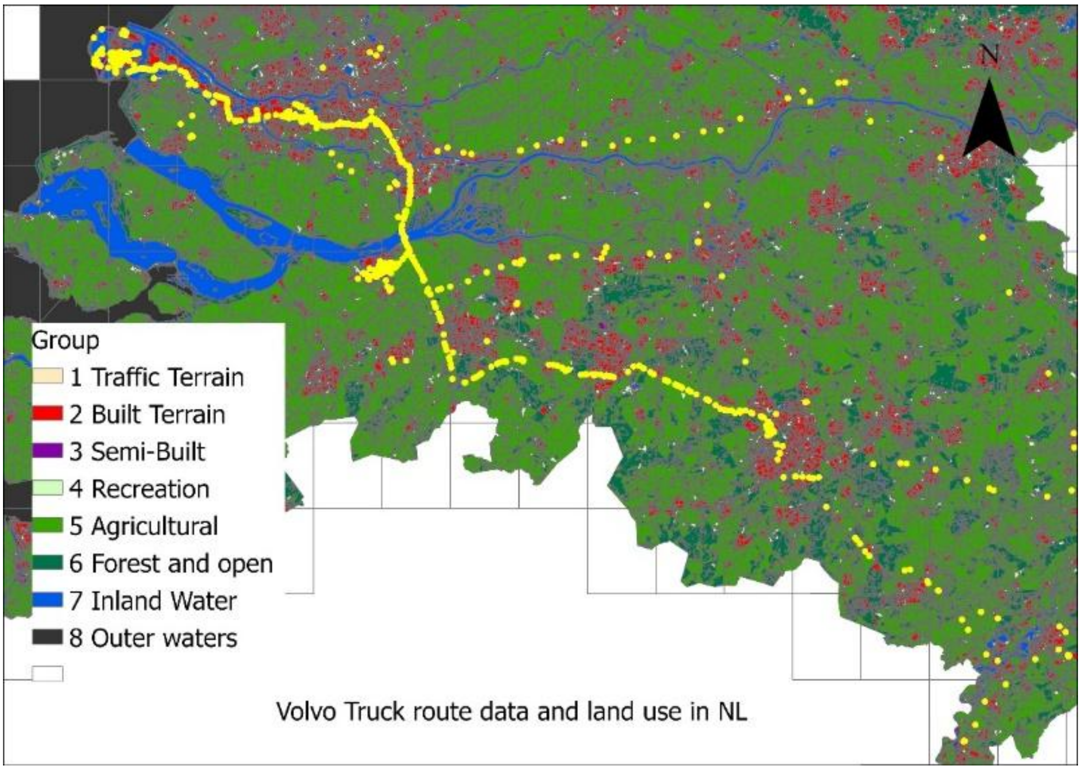


Figure 49: Volvo truck routes

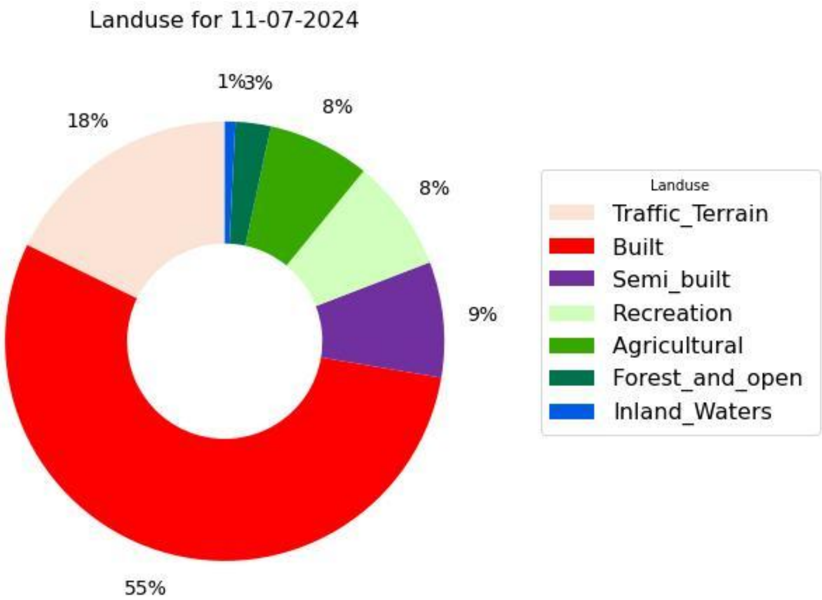


Figure 50: Land use along route of Volvo truck on July 11, 2024

This shows that for the time period the truck was located in urban areas for 53% of the time the remaining time in more open areas. This would fit best to the vehicle archetype HT11 or HT22, regional distribution, for which we have used the semi-urban shading function. For the time period under investigation, this function has an average shading loss of 17%.

The total KNMI irradiance for the period was 168.5 kWh/m2. In the same period, the irradiance on the truck was 125.4 kWh/m2. This results in a total shading factor of 26%, which is much higher than the shading factor of 17% used in Chapter 1. However, the measured irradiance loss includes the times when the truck was parked in the shade, which might not reflect the typical irradiance conditions of a truck with VIPV. Splitting into driving or stationary shows that the shading loss is 32% when stationary and 10% while driving, see Figure 51. This is to be expected as the truck will be parked mostly for loading or unloading in which situation buildings will be around that cause shadows on the truck.

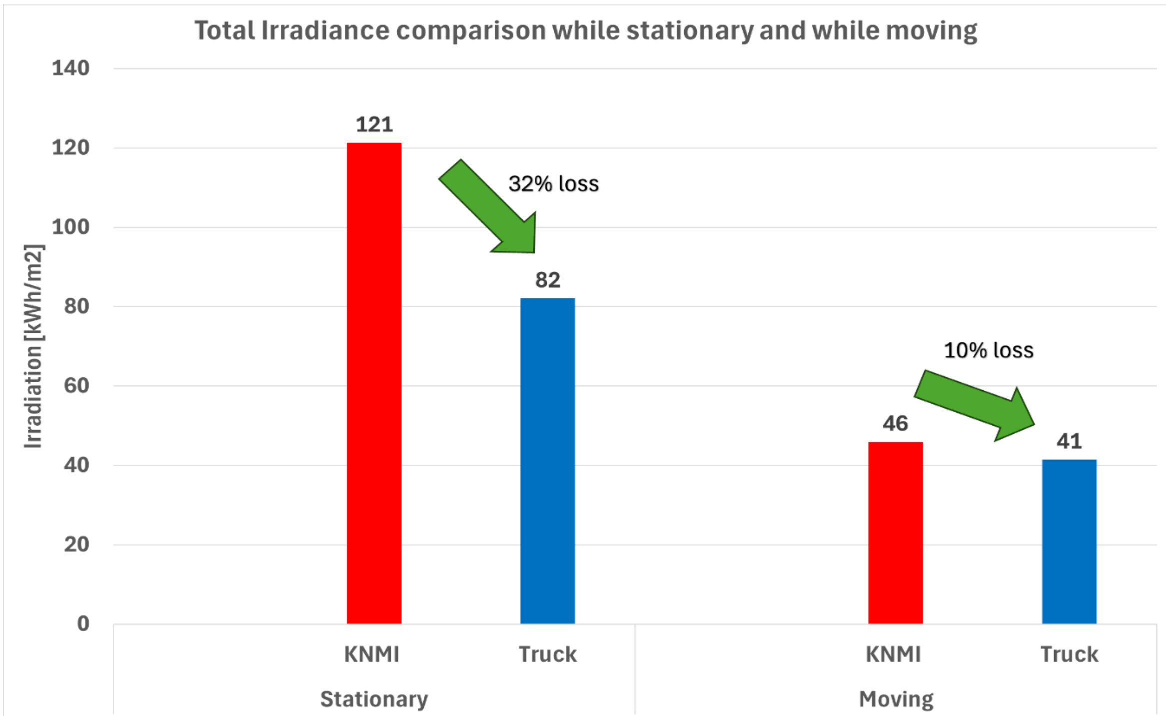


Figure 51: Total irradiance comparison

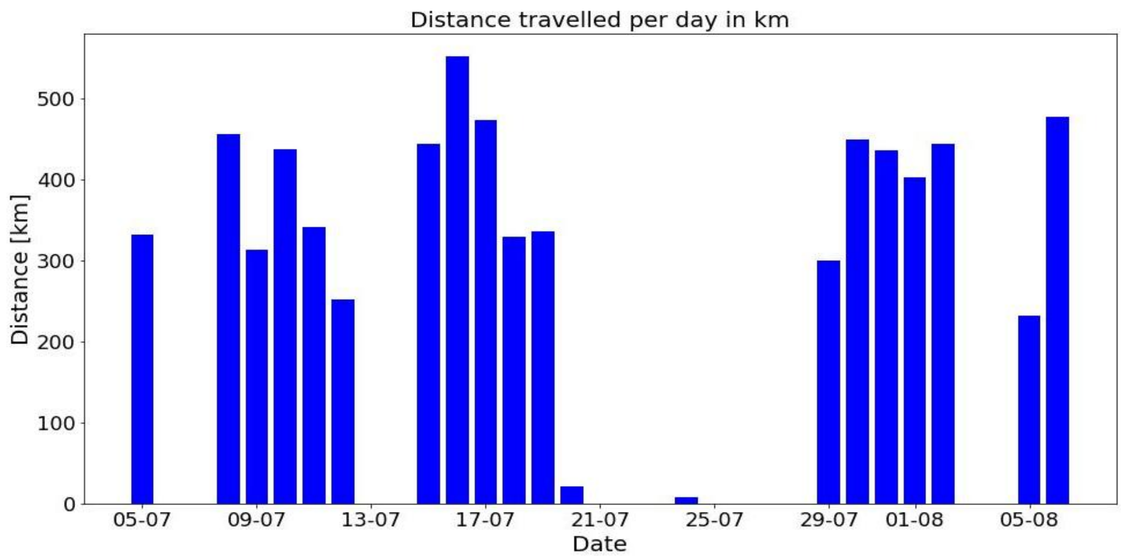


Figure 52: Daily kilometres travelled by the Volvo Truck during the test period

Looking further into the data we observed that there were several days that the truck was not moving at all, see Figure 52. Taking only those days into account when the truck was driving and calculating the irradiance loss results in Figure 53. As can be seen there are 2 days where the truck irradiance is higher than the KNMI irradiance (shading loss < 0%), which might be due to the tilt of the sensor. There are also 2 days where the shading loss is >20%. On these 2 days, the irradiance is rather low and there is probably quite some diffuse light that is scattered more by surrounding objects as well.

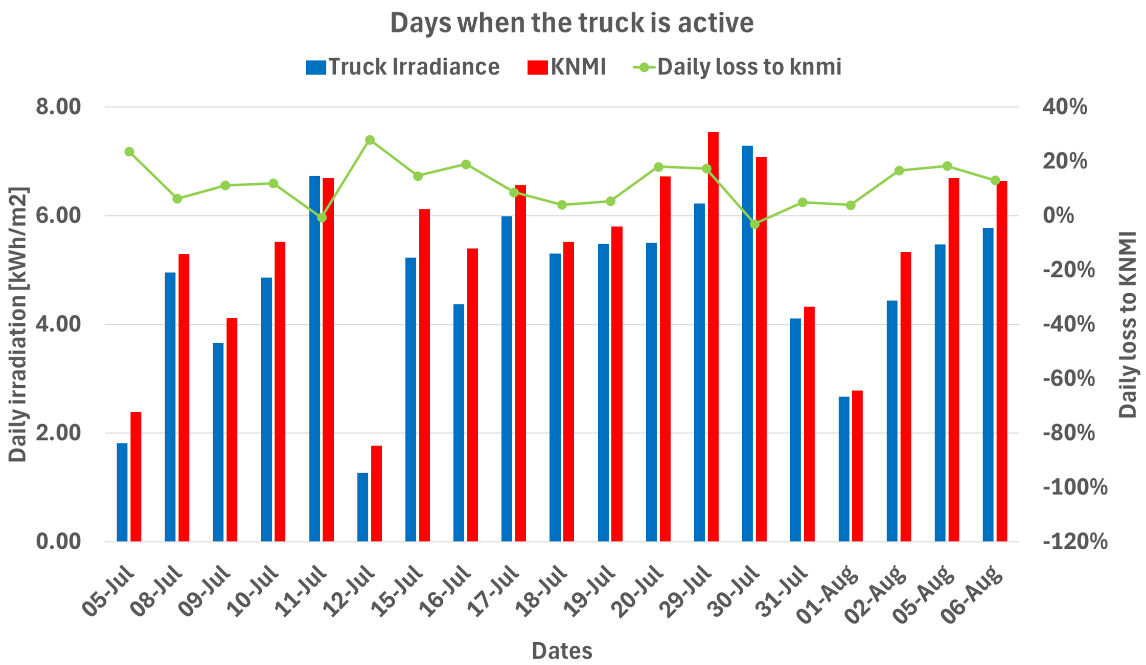


Figure 53: Truck irradiance loss results

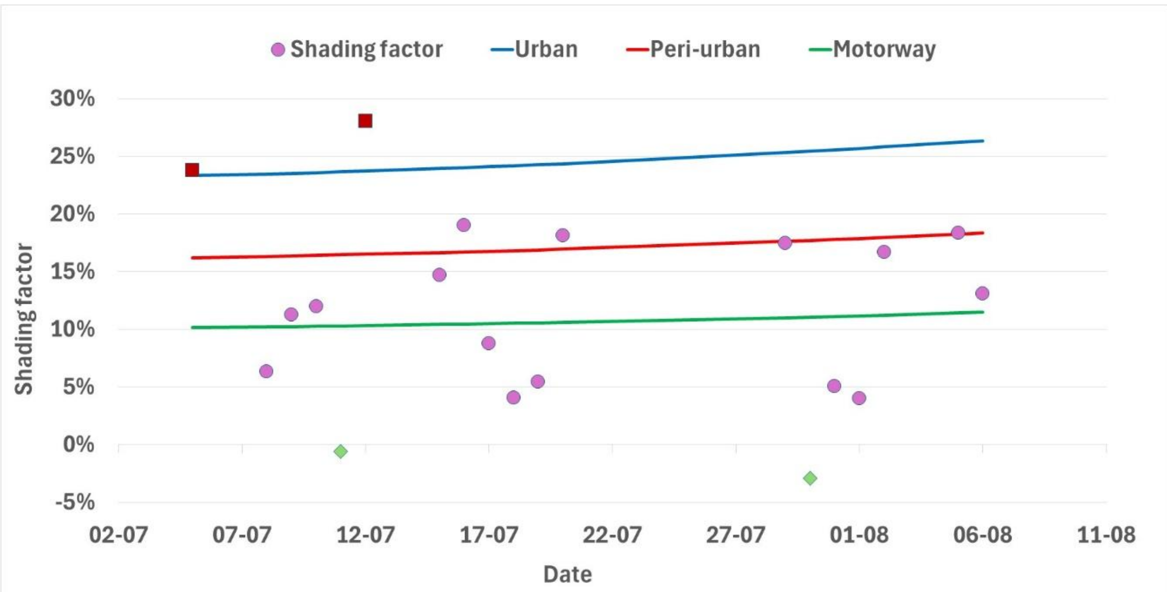


Figure 54: Truck shading loss comparison. Red squares indicate the outliers resulting from the tilt of the sensor and the green diamonds indicate the 2 outliers due to the low irradiance conditions in combination with reflection of the diffused light.

The same data is represented in Figure 54 together with the irradiance model as used in Chapter 1. Ignoring the two outliers on top and bottom (red squares and green diamonds), we can see that the majority of the shading loss factors are somewhere between 5 and 20%, which ranges from 'lower than the urban shading model' to 'roughly similar to the peri-urban shading model'. As mentioned above, based on the average terrain type the truck is traveling in, we would have assigned the peri-urban shading model, and thus would underestimate the irradiance (overestimate the daily loss).

Zooming in further into the irradiance losses per trip, we chose July 30, a sunny day, and looked at the irradiance losses in comparison with the terrain type. Figure 55 gives the truck irradiance in red, the KNMI irradiance in blue and the driving and parking moments in purple.

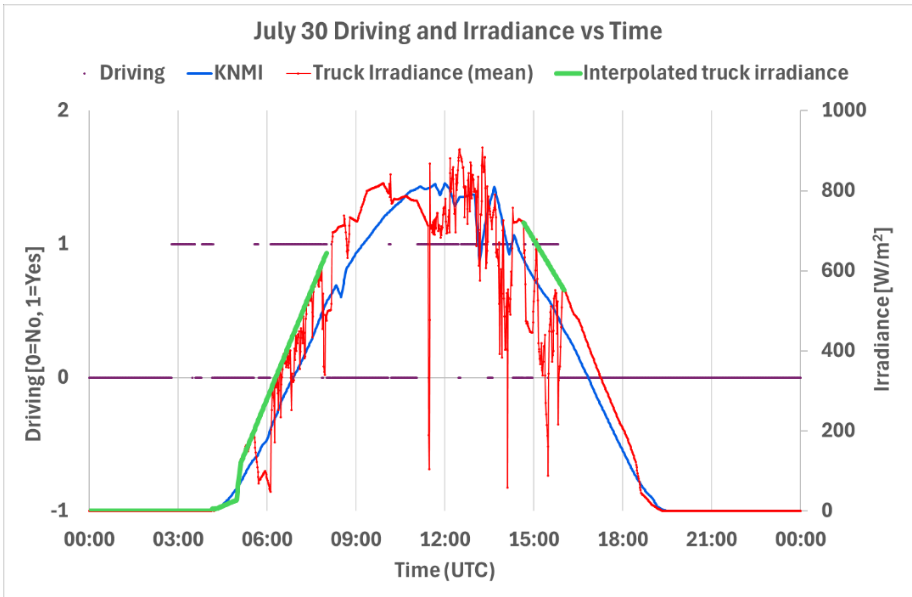


Figure 55: Irradiance comparison for one day truck route 30th of July

As the KNMI data is lower than the truck data, which we think is due to the tilt of the sensor, we used the envelope of the truck data as the reference irradiance (green lines). The first trip we zoomed into, around 6AM, gives a 11% shading loss. Looking at the terrain distribution for this trip, Figure 56 left, we see that 9 % of the time the truck was in build terrain, and the remainder in open terrain. This would relate to the 'long distance highway' shading model of Chapter 1, which uses a shading loss of 11%. This matches perfectly with the measured shading loss.

Next, we looked at the trip around 3PM. Here a shading loss of 31% was derived from the measured data. The corresponding terrain data for this trip can be seen in Figure 56 right. For this trip the truck travels for about 25% of the time in urban areas and the remainder of the time in open areas. Again, this would relate to a peri-urban shading model in Chapter 1. The shading factor for that model on July 30th is 18%, which is much lower than the 31% of the measurement. This is due to many overpasses and high slopes along the route.

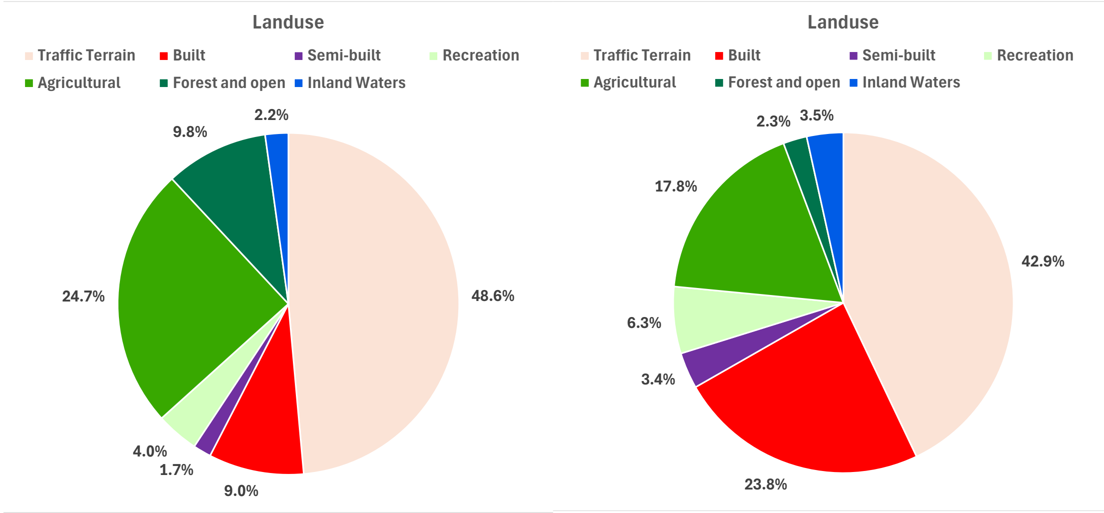


Figure 56: Land use type for two truck trips: July 30 at 6AM ad July 30 at 3PM

Based on the Volvo data, it can be concluded that it is very difficult to determine a generic shading factor. It strongly depends on the specific route in combination with the time of day. Only by averaging many measurements, a more general irradiance factor can be determined. For this much more measurements are needed.

Luton truck

The second data set that was used for the irradiance model validation was the data from the Luton truck from IM Efficiency (see Table 86). Data for this truck has been collected between 14/2/2024 and 9/10/2024. A first analysis was done for August 14 2024, which was a rather sunny day. Figure 57 shows the truck data together with KNMI data and data from the Meteonorm dataset. As can be seen there is a good overlap between the KNMI data and truck data.

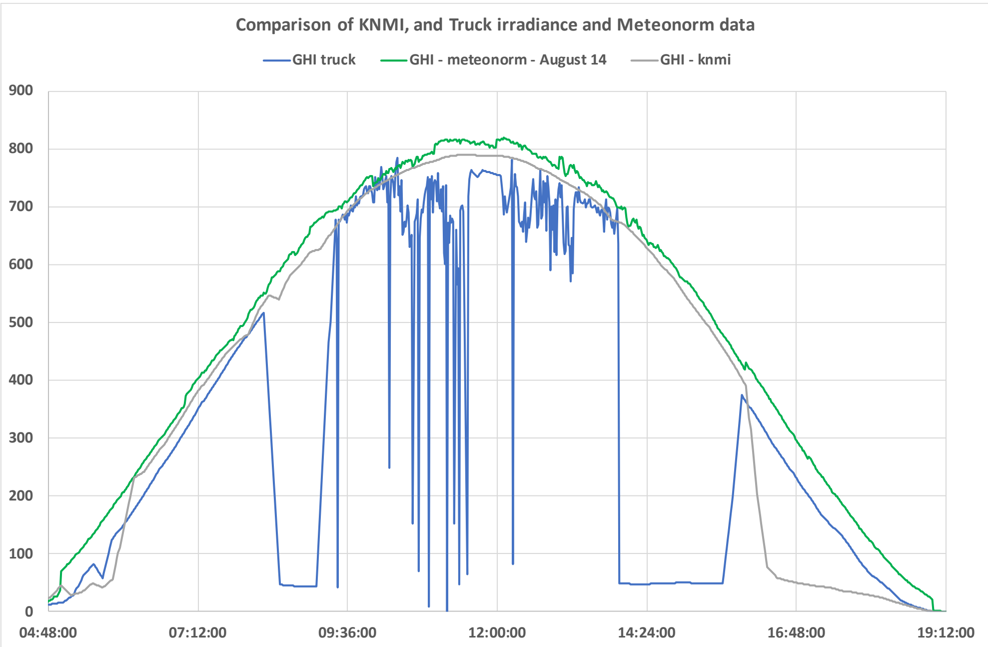


Figure 57: Irradiance data for Luton truck

There are two large drops in truck irradiance, one in the morning around 9 AM and one in the afternoon around 2PM. From the GPS data of the sensor it is known that the truck was not moving and was parked in the shade. Comparing the KNMI and truck irradiance for this day gives a 29% shading factor. Based on the trip of the truck we would have used a peri-urban shading model approach with a shading factor of 19% for August 14. The large difference is due to the shading during parking. Excluding the two dips where the truck was parked reduces the shading factor to 15%.

2.2.5. Measurement results compared to the modelled shading factor

In the Chapter 1 we have reported on modelling of the various archetypes with respect to range extension, reduced charging moments etc. The irradiance model used in the modelling was a seasonable shading model for 3 different road types.

By plotting the measured irradiance factor we can now compare if the assumptions in the model are valid. Figure 58 shows the irradiance factor based on all the data for the three different road types together with the modelled irradiance factor. As can be seen, the measured irradiance factor shows much less seasonal dependence compared to the model. For motorway and semi-urban the irradiance is lower for the whole year compared to the model assumptions, whereas for urban the model in general overestimates the irradiance in summer, and slightly underestimates the irradiance in winter.

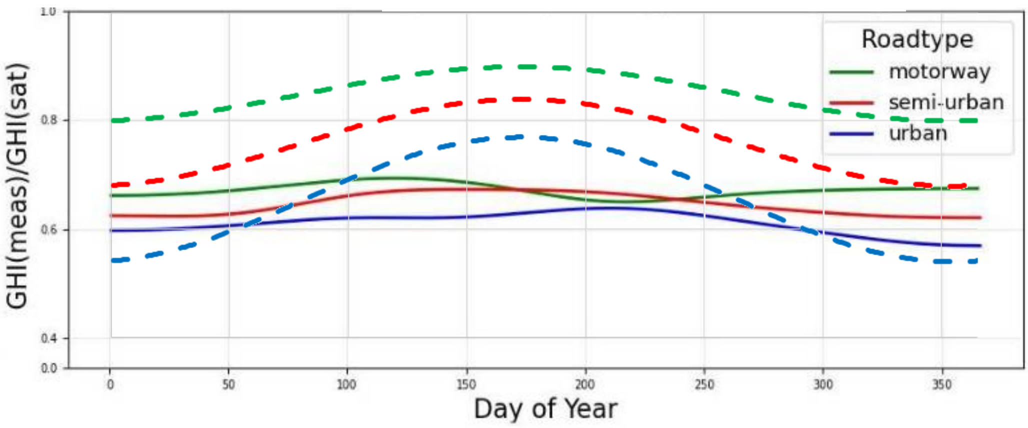


Figure 58: Total measured seasonal irradiance factor for the road types. Solid lines measurements, dashed lines model

The seasonal irradiance factor distribution for the specific archetypes LP22, HB11 and HT22 is shown in the following figures. For the passenger car, LP11, with 70% circulation in semi-urban environment, there is almost no measured seasonal effect, and the model assumptions overestimate the irradiance on the vehicle for motorway and semi-urban. For urban, the model overestimates the irradiance in summer and underestimates during winter.

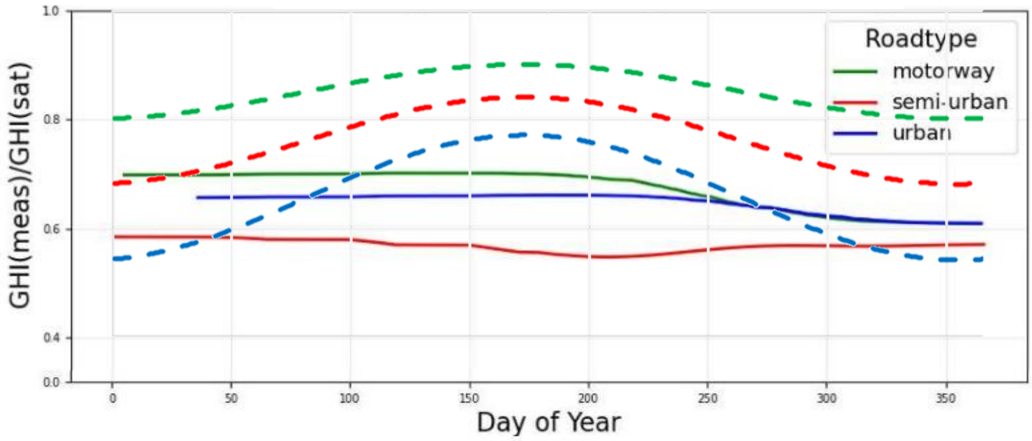


Figure 59: Measured seasonal irradiance factor for LP12. Solid lines measurements, dashed lines model

For the low floor bus, HB11, circulating 80% in an urban environment, the seasonal pattern found is quite similar to the one used in the modelling, although less pronounced. Here again, the motorway and semi-urban model overestimate the irradiance, whereas the urban matches quite well on average.

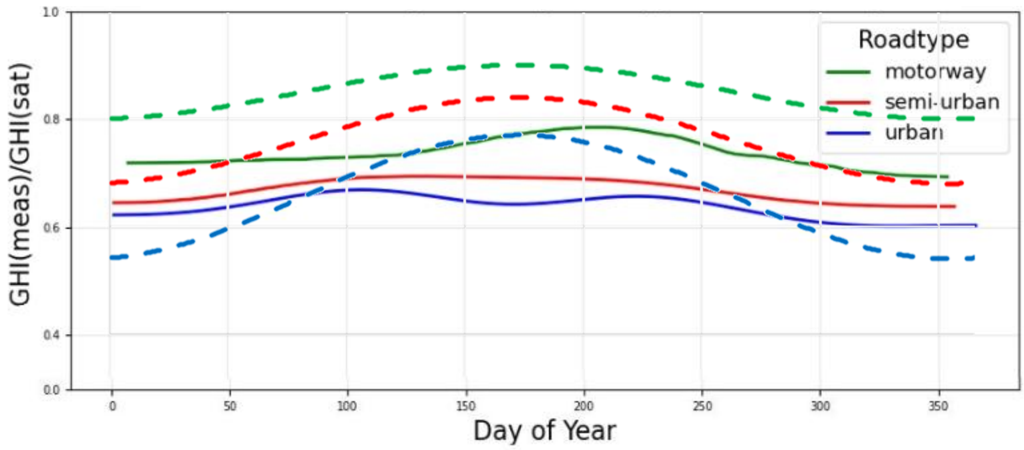


Figure 60: Measured seasonal irradiance factor for low floor bus HB11. Solid lines measurements, dashed lines model

For the rigid truck with 43% on urban, 31% on semi-urban roads and 26% on motorways, HT22, all three curves for the irradiance factor are close to each other. The measured urban irradiance is higher than the modelled one, so the model underestimates the irradiance, while the motorway and semi-urban models overestimate the irradiance.

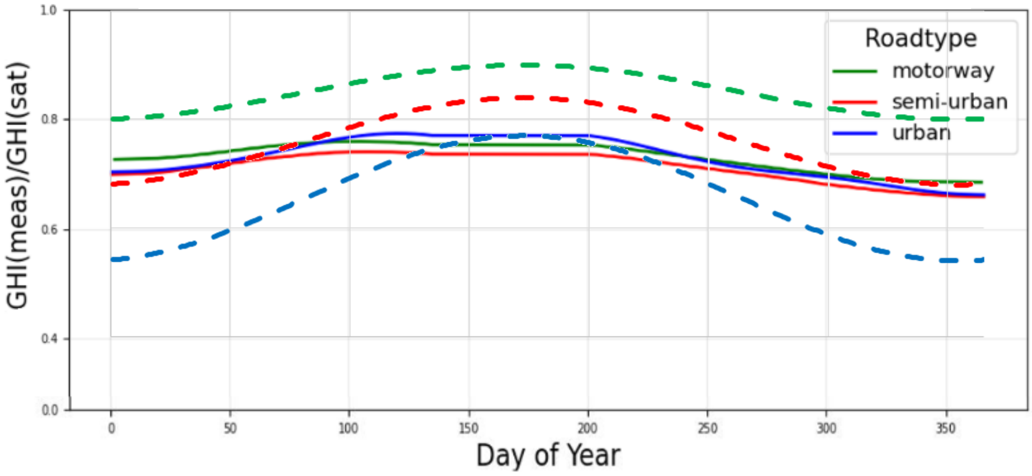


Figure 61: Measured seasonal irradiance factor for rigid truck HT22. Solid lines measurements, dashed lines model

In conclusion it can be seen that for all the archetypes analysed, the irradiance model overestimates the irradiance in motorway regions. The semi-urban irradiance model in general also overestimates the irradiance but in winter the match can be quite good depending on the archetype. The urban irradiance model can either over- or underestimate the irradiance depending on the season. It can be concluded that the irradiance model, besides having a seasonal and road type dependence, seems to strongly depend on the archetype as well. This makes it difficult to use a generic seasonal shading model.

2.2.6. Energy weighted shading factor case studies on individual vehicles

In order to see the difference between the use of the Shading factor and energy weighted shading factor in more detail, especially the influence of parking, we have selected a few case studies. The first one is the case study of a public bus in Bavaria that is parked outside, the second one is a case study of a passenger car.

Public bus with a regular driving route and parking situation outside

This is a public bus in Hof, Bavaria, with the following activity radius in Sep 2024:

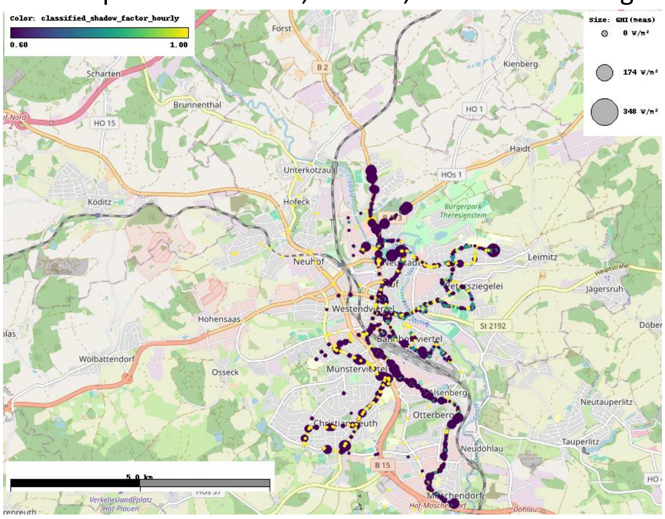


Figure 62: Activity radius of public bus in Hof, Germany

To start with, we look for a day with the proportion of satellite irradiance to clear sky of more than 90% (CLS ratio), so basically an almost cloudless day. The measured irradiance, the satellite derived irradiance and the clear sky values on 21.9.2024 are shown in Figure 63. We find an ESF of 33% and so a PV system would have produced 33% less than on a clear sky day. The route travelled on this day is shown on the right, with an excerpt below.

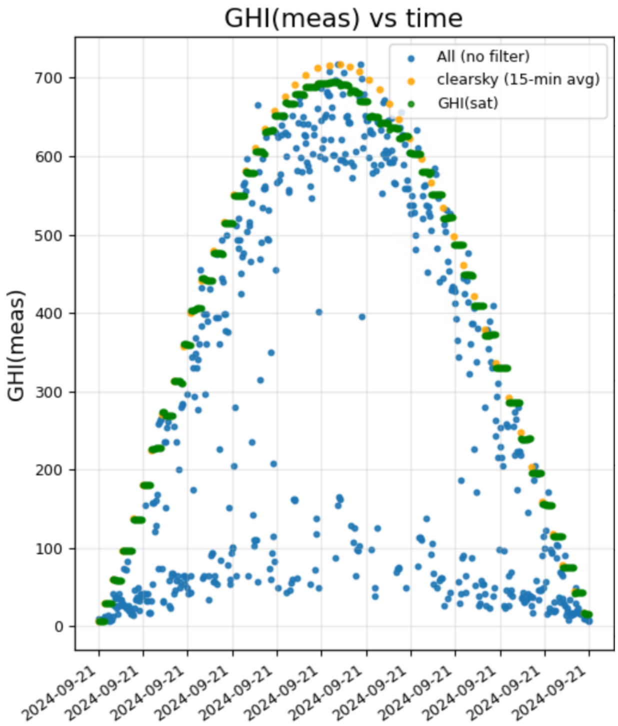


Figure 63: GHI & CLS of public bus

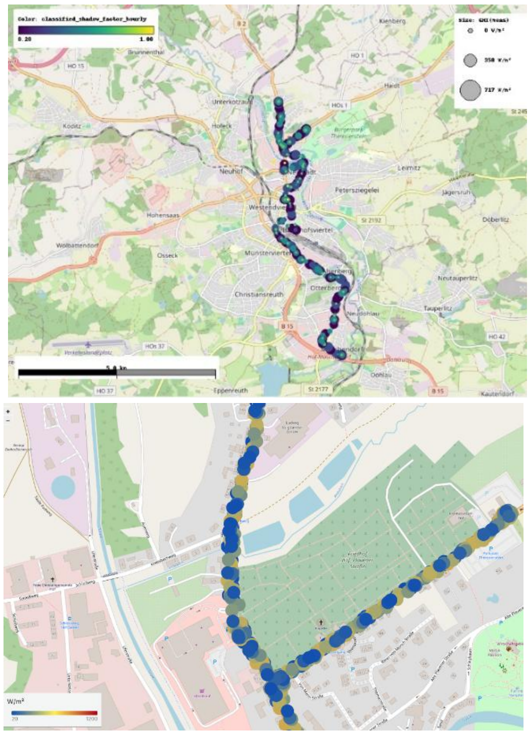


Figure 64: Bus track with ESF (up) & GHI (below)

One important research question is the significance of parking situations on the ESF. For this first case of the public bus, we are looking at a 4-day period from 6-10.1.2025, when the vehicle was not moving, but parked (Figure 65 and Figure 66) resulting in an ESF of 24% (total=stationary).

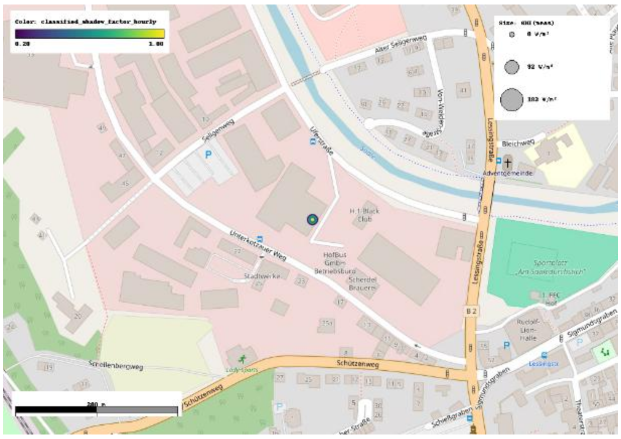


Figure 65: Parking situation on map

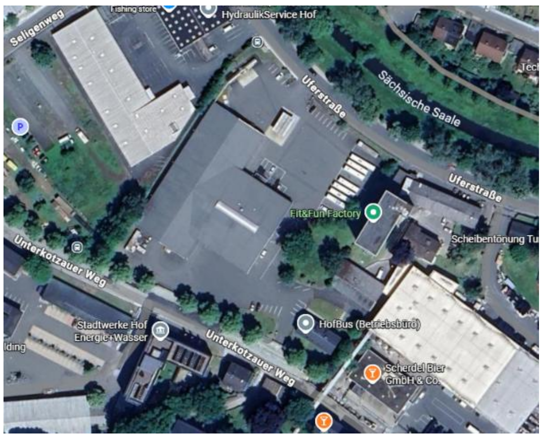


Figure 66: Parking situation aerial photo

Passenger car parked outside

Between 8-15.5.2025, this vehicle in its parked situation had an ESF of 63.2% (total= stationary)

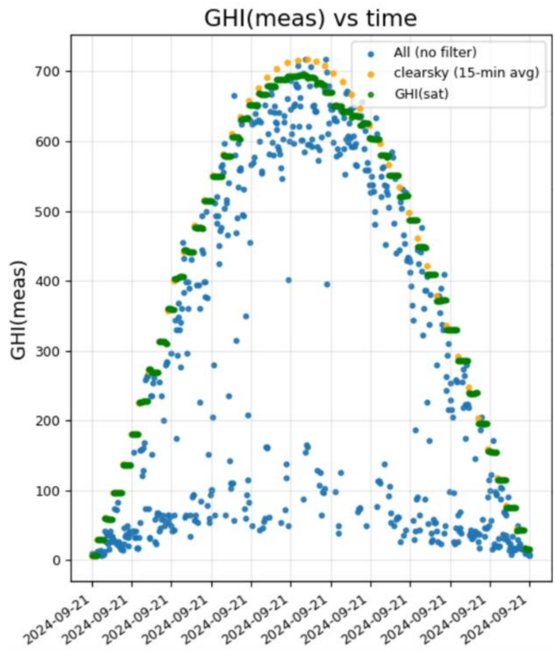


Figure 67: Typical day, Renault Clio Bonnie; ESF = 63.3%

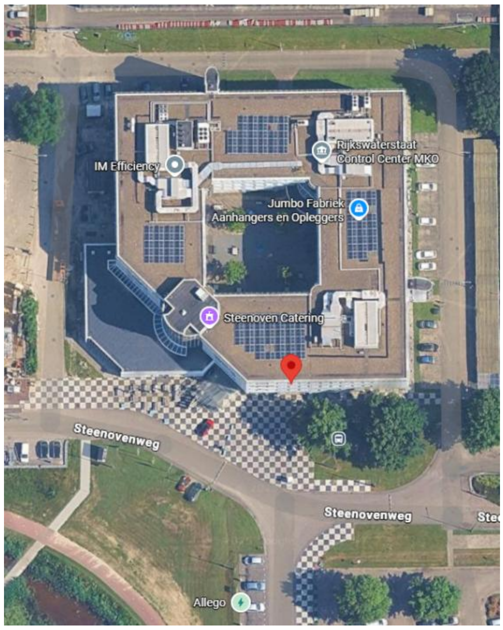


Figure 68: Parking situation Renault Clio Bonnie

In Figure 67 we can see very clearly how the vehicle is parked in the shade in the mornings and afternoons which leads to a very high ESF of 63.3% for the parked days. In the table below the effect of the parking situation on the overal ESF is seen for a longer time range (1 month / 2 months).

The vehicle in A2 was parked in total on 28 days in the period April/May 2025.
The shade in a parked situation has a big influence on the overall ESF even in a longer time period.

Table 27: Longer times scale (27 days to one month): ESF with parked /moving

Case	Time	ESF total	ESF Moving	ESF Stationary	Parked/ total days	Movement
A1 public bus	06.01.25-10.01.2025	24%	0	24%	4/4	Stationary
A1 public bus	27.12.24-22.01.2025	24.3%	29.3%	26.2%	18/27	Mixed
A2 passenger car	08.05.25-22.05.2025	63,1%	0	63,1%	14/14	Stationary
A2 passenger car	01.04.25-29.05.2025	55,1%	15,4%	55,2%	28/58	Mixed

Energy weighted shading factor case studie using all data

Using all data passing quality criteria for horizontal units

Under the mentioned conditions, sun elevation >= 10° and measured irradiance >= 1W/m^2, we find a total of 2,626,030 data points. For all these datapoints we assigned a road type according to the LCZ approach as explained above and matched it to one of the archetypes. In Table 28 resulting average ESF for each archetype is listed, together with the number of datapoints on which the analysis has been executed, as well as the ESF for the moving and stationary states. We can see that the archetypes LP11, LP21 and HB11 (indicated in light green, moving in a mostly urban environment) all experience around 2 times higher ESF in stationary compared to moving situations. The LP10 also moves mostly in urban areas, but this data relates to a single vehicle, which might make the results very specific.

For the trucks we have to note that the HT2*-archetypes (tractor-trailer) were only covered by the DAF truck-trailers and therefore direct comparisons between HT1* and HT2* (rigid truck and tractor-trailer) archetypes are difficult because of a lack of data variability.

Table 28: Data availability and ESF (total, stopped, moving) for SolarMoves archetypes

Archetype	Type	#	Average ESF	Moving ESF	Stationary ESF
LP10	Small passenger car Occasional use	13192	20.9%	26.60%	21%
LP11	Small passenger car Urban commute	18764	75.6%	40.90%	76%
LP12	Small passenger car Peri urban commute	40249	38.2%	28.20%	36%
LP21	Medium passenger car Urban commute	17066	24.4%	14.2%	29.3%
LP22	Medium passenger car Peri urban commute	84292	24.6%	17.6%	25.6%
LV21	Large van Local distribution	57798	30.1%	18.4%	30.8%
HB11	Low-floor bus Urban public transport	347311	18.1%	11.4%	20.8%
HB12	Low-floor bus Peri urban public transport	381740	19.5%	4.4%	22.9%
HT11	Rigid truck Urban distribution	147356	38.7%	44.7%	38.9%
HT12	Rigid truck Regional distribution	70889	42.2%	57.4%	40.6%
HT22	Tractor-trailer Regional distribution	166032	10.3%	11.6%	13.0%

Since we introduced a new way at looking at vehicle shading from an energetic point of view (ESF) as opposed to an “geometric” way (SF), it interesting to see the effects of these different approaches for a whole year. In Table 29 we list ESF and SF per road type and moving state. As can be seen, the shading factor is higher than the ESF.

Table 29: Energy shading factor and shading factors

All data	**ESF**	**SF**
Urban	19.4%	30.1%
Semi-urban	13.3%	23.5%
Motorway	19.0%	29.3%
Data selection		
Moving	16.3%	18.7%
Stationary	19.5%	32.7%

2.2.7. Conclusions and recommendations

Sensors were developed, tested and calibrated by Fraunhofer ISE and have been installed on various vehicles of (partners of) Lightyear, IM Efficiency and Sono Motors. The vehicles chosen differ from the shortlist due to lack of availability of the preferred archetypes. Data acquisition has started, and the first results have been analysed, showing that the sensors on the sides of the truck in general obtain about 50% of the irradiance of the top sensor. The measured irradiance data can be used to determine the possible energy generation by VIPV, as well as deriving the losses due to shading.

This latter has been done by comparing the measured irradiance with MeteoSat data. For this a Methodology for Satellite Data Evaluation has been developed, and the methodology has been used and the results have been compared to the measured irradiances. Using open street map data, the difference in satellite and truck irradiance per and use type has been derived and compared with the general shading model as used in the modelling in phase 1. There is a good similarity in the trend over the year but the on-board sensor derived data show a higher loss. Distinguishing between driving and parking, it has been observed that while driving, the shading losses are lower than anticipated in the model, whereas during parking the shading losses are higher. This is probably due to the fact that the vehicles have been parked in the shade in many situations. It shows that behavioural aspects are also important to take into account and operational guidance is needed to instruct drivers to park in the sun whenever possible.

An accurate prediction of the irradiance on the vehicles is essential for the prediction of the energy generation from VIPV. One can identify two different scenarios:

1. Actual irradiance on individual vehicle level during the day: important for planning of e.g. logistics companies.
2. Yearly/monthly Irradiance on archetype level: important for policy, fleet owners, OEM's.

For the first scenario, the shading factor at the various route points needs to be identified, which needs a very detailed shading model. For the second scenario a more general shading model is sufficient. Such a model does not take into account the specific shading factors at each route point, but takes the average for trips, days, months or years. So depending on the specific goal, very detailed or more general shading model need to be used.

For the SolarMoves project a general shading model has been used in the first phase. And has been validated in the second phase. This data analysis of the irradiance sensors and the comparison with the irradiance model used in the first interim report show that it is extremely difficult to make an accurate prediction of the actual irradiance on the vehicles at a specific point along the route and thus of the actual electricity production of VIPV. The following potential sources of inaccuracy have been determined:

a. The shading loss at a specific route point on clouded or partially clouded days cannot be determined as the reference irradiance is always influenced by the fact that the reference sensor is at a different location compared to the truck sensor. Irradiance dips due to clouds occur at a different time so the ratio of the reference dataset to the vehicle dataset does not reflect the shading at that time. Instead an average shading loss for the day can be derived.

b. This also means that we cannot relate a shading loss to a specific land use type on these kind of days, but only an average shading loss for the whole day and thus for the combined road types of the trip.

c. The derived general shading loss is influenced by the conditions during parking. Often the parking is done in the shade, which strongly increases the overall shading factor.

d. The derived general shading loss for a day, and thus also on a yearly basis, is influenced by the different land use types during the trip. These are very location specific and thus differ per region and country.

e. When looking at individual trips and taking into account the major road type, in some cases a good match is achieved between the shading model used in phase 1 and the measured shading loss. However, there are also situations where there is still a large difference. E.g. for highway areas with slopes or noise barriers next to the highway or many overpasses, that cause shading, especially in the afternoon.

Although there are in some cases substantial differences between the measured and modelled shading factors, the results indicate that in most situations the irradiance in the model was underestimating the actual irradiance. But only if parking in the shade is ignored. Of course, a vehicle with PV integrated should preferably be parked in the sun, but this is not always possible at docking locations for loading and unloading.

Although the above-mentioned inaccuracy sources a and b relate to scenario 1, they are at this stage also important for scenario 2, as the shading factor per land use type is needed to construct the general shading factor for a specific archetype. There are several recommendations to improve the shading model.

1. In the first phase, the trip definitions have been made based on a distribution of road types, see Table 30 for an example. In the shading model also a combination of the different road type shading models can be used. The challenge will be to distribute them over the days and year in order to be representative for the vehicle archetype.

Table 30: Example distribution of road types

Vehicle type	Vehicle class and type	Use pattern	Description	km/a	Urban	Rural	Moto rway
LP10	Small passenger car	Occasional use	Cars that are driven a few times a week	3795	21%	42%	37%
LP11	Small passenger car	Daily urban commute	Cars that are driven mostly in urban areas on a daily basis	3894	70%	10%	20%
LP12	Small passenger car	Daily peri-urban commute	Cars of people that live outside the city and/or use their car on a daily basis to commute to rural areas	8099	20%	70%	10%
LP13	Small passenger car	Long-distance highway travel	Cars that commute most of their mileage on motorways for long-distance travel, due to business and holidays	14479	10%	20%	70%
LP14	Small passenger car	Car sharing		16237	26%	33%	42%

2. Another option is to determine the shading factor per route type to be able to build a more accurate general shading factor from the trip definitions. The measured irradiance datasets can be used to derive these factors. Here two options can be investigated:

   Use the mayor land use type of each route point to set the road type at that point. Use the ratio between the KNMI, Meteonorm or satellite data and the truck data to determine the shading factor for that land use type. This has been shown above but needs more data to determine the shading factor more accurately.

   Determine the land use type distribution of each route point. E.g. a route point at the border of a built area can be 50% build land use and 50% agricultural land use (see Figure 69). Determine the shading factor by performing a multiparameter fit on the ratio between the KNMI, Meteonorm or satellite data and the truck data.

3. For the model validation more data is needed to be able to determine a general shading factor. More data means that deviations due to e.g. parking in the shade, highways with overpasses and side slopes, will be averaged out. This will be partly done in the remainder of the SolarMoves project, but it is important to continue data analysis to improve the accuracy of the models.

Having validated the irradiance and shading inputs in Section 2.2, the analysis now moves from radiative inputs to vehicle-level energy outcomes. Section 2.3 therefore focuses on validating the MEO vehicle energy consumption model by comparing simulated results with measured energy use from real vehicles.

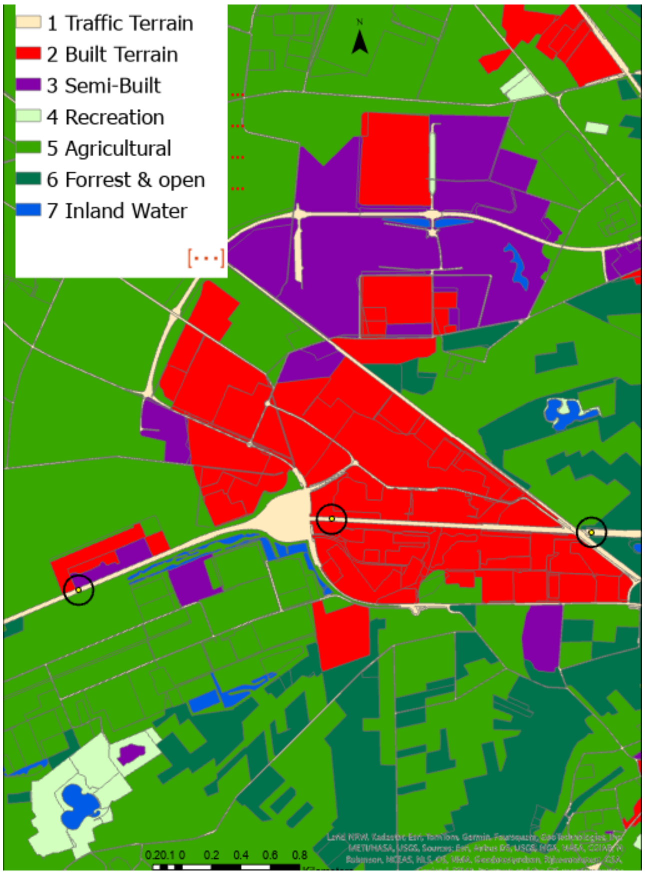


Figure 69: Example of the different land use types at the position of a route point. Refinement of the model can use either the mayor land use type of a point or the fractions of the different land use type at that point

2.3 MEO Model validation

This paragraph validates the vehicle energy consumption model by comparing its predictions against real-world measurements for a passenger car, a van, and a heavy-duty vehicle. While the dataset is limited and the tested vehicles do not fully align with the defined archetypes, the objective is to assess model accuracy rather than archetype representation. To ensure meaningful validation, actual vehicle parameters—such as mass, frontal area, and, where available, air drag coefficient—were used as inputs in place of generic assumptions.

2.3.1. MEO model validation for an electric truck

From other projects, TNO has access to energy consumption, mileage and tractor-trailer mass data for several Volvo FM Electric trucks that are being monitored. The mass and velocity of the vehicles are available on a per-minute basis, but the actual energy consumption data is limited to one value per day – insufficient to validate the model. As one of the trucks was kindly made available by the owner for the SolarMoves solar irradiance measurement campaign, we could fit a sensor with the data logger that contains a GPS device, from which a 1 Hz velocity signal can be derived: sufficient to also calculate acceleration and deceleration, provided there are no large differences in altitude between start and end of the trip. Fortunately the truck drives mostly in the Netherlands.

Several days with sufficient driving, varying payload and varying average speed were selected. This would allow us to derive insight in the cause of potential model deviations. The energy consumption model MEO was fed with the GPS based speed trace, known vehicle mass from the Volvo Connect portal (one value per trip) and the vehicle specifications. The energy consumption as calculated was compared to the energy consumption as reported by the vehicle itself through Volvo Connect. Checks were done on total daily distance and daily battery SoC change.

Problems were encountered in the speed trace data from the SolarMoves solar irradiance sensor (selected days unsuitable). A single day was instead selected by Fraunhofer, having the least issues. Several trips were run at varying payload. The model results per trip and total results (bottom of the table) are shown in Table 31.

Table 31: Results of comparison between measured and modelled energy consumption of Volvo FM Electric on a single day

Trip	Average speed when moving [km/h]	Total energy (kWh)	Total distance (km)	Average total weight (ton)	Total energy (model) [kWh]	Total energ y (real) [kWh]	Model energy cons. [kWh/km]	avg. Ambient temp [°C]
Trip 1	76.4	79.7	77.1	20.5	80.1		1.04	14.5
Trip 2	69.5	35.6	37.0	16.0	35.9		0.97	15.1
Trip 3	21.5	5.3	1.1	17.2	5.6		5.27	15.7
Trip 4	64.2	45.8	43.4	17.5	46.2		1.07	15.6
Trip 5	44.5	32.7	16.7	36.1	33.0		1.98	15.7
Trip 6	58.9	41.1	40.2	20.2	41.2		1.03	15.9
Trip 7	41.7	20.6	19.0	17.4	20.6		1.09	16.3
Trip 8	29.9	121.8	74.0	41.7	121.8		1.65	16.9
Trip 9	29.9	5.4	4.8	22.0	5.4		1.12	16.4
					Sum	**Sum**	**Average (Total Energy / Total distance)**	
					389.8	410.9	1.24	

The results show a small underestimation of the model of approximately 5%. However, accounting for the fact that the sensor-based speed data represented a driven distance 5% lower than reported by the truck itself, both model and measurement result in a consumption of 1.24 kWh/km.

Earlier exercises have shown a variation of the model results that could be explained by an offset probably due to underestimation of loss factors in the truck by the MEO model. However, better data would be necessary to analyse this further.

2.3.2. MEO model validation for a passenger car

To validate the MEO model for a passenger car, the Lightyear 0 was chosen, in the light of data availability. The fact that this vehicle is outside the specifications of the archetypes is not posing limitations to this exercise, since we are evaluating the model, not the archetype definition. Lightyear provided specifications of the vehicle such as mass, air drag coefficient, frontal area, motor efficiency and other efficiency factors. These were subsequently configured in the model.

Data was made available by Lightyear for four days of driving with the Lightyear 0, on a 1 Hz basis. The data encompassed velocity and change in state of charge of the high voltage as well as the low voltage battery, in hundredths of percents. The results for one of the four days is shown in Figure 70.

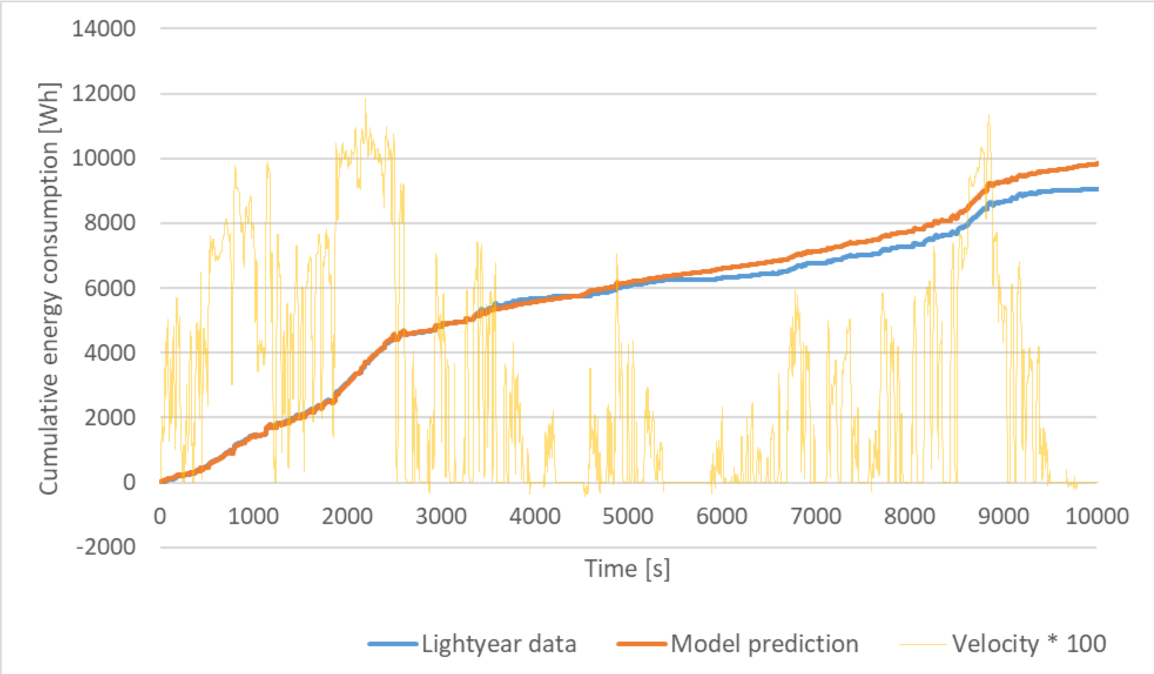


Figure 70: Comparison of measured and modelled energy consumption of Lightyear 0 on 28th October 2024 over a distance of 83.5 km

For the selected day, the model overestimates the energy consumption by 9%. From the velocity line (yellow) and the deviation between the measured Lightyear data and the model prediction, it can be seen that the overestimation predominantly occurs when the vehicle is stationary or driving slowly. This indicates that the auxiliary consumption is overestimated for the Lightyear. That is not surprising, because in the model a fixed idle energy consumption value is assumed, derived from measurements on a few mass produced electric vehicles. From discussions with Lightyear, their idle consumption is approximately half the value used in the model.

Some overestimation is also seen at longer distances at highway speeds. This results in the larger difference for the trips on 7th November; see Table 32 for details.

The passenger vehicle energy measurements show about 10% solar gain compared to the model predictions. The validation of the model for passenger cars lead to the following conclusions: The model overestimates the passenger car energy consumption for the test days by 4 to 30%, dependent on the trip composition.

For the test of 5 November, no analysis could be done, because the signals from the Lightyear 0 showed inexplicable behaviour. Further analysis pointed out that the vehicle has been charged in the meantime, exhibiting as a negative energy consumption. After correction, the model results are still overestimated by 49% (see Figure 71).

Table 32: Results of comparison between measured and modelled energy consumption of Lightyear 0 on four days.

	23 October 2024	28 October 2024	5 November 2024	7 November 2024
Time (min)	52	168	43	226
Distance (km)	21.3	83.5	24.3	187.4
Average ambient temperature (°C)	15	15	8	5
Measured consumption (kWh)	2.04	9.05	2.13	14.46
Modelled consumption (kWh)	2.12	9.84		19.86
Model overestimation	3.9%	8.7%		37% (30%)
Notes			Error in input data: SoC in measured data jumps up a few times in a single second	30% without 22 min stationary (model assumes vehicle is on)

An analysis was made by TNO and Lightyear, comparing in detail the energy consumption and underlying parameters such as vehicle speed and temperature. It became apparent that, amongst other things, the model deviates when the vehicle is stationary. Four conclusions can be drawn from the analysis:

1) The Lightyear 0 has very low idle consumption at 180W. The model assumes 900W, which is based on measurements on mass produced cars in the Green NCAP programme.
2) The Lightyear 0 has 0W standby consumption, as the test vehicle is fully shut down between the measurements.
3) The Lightyear 0 prototype used for the tests has no air conditioning/heating consumption. The model assumes consumption relative to the ambient temperature.
4) The model underestimates the consumption at high speeds (about 5% at 100 km/h), despite the fact that the actual Lightyear Cd value and frontal area were used as input.

The 0 W readings seen in some measurements occur because we frequently fully power down the Lightyear 0 test vehicle when it is parked. This involves a complete 12 V battery disconnect, meaning that no systems remain active. We do this deliberately, as the vehicle is one of the early prototypes and is not required to remain in a standby state.

The low auxiliary power consumption of approximately 180 W (compared to an industry average of ~900 W) is primarily the result of a strong design focus on minimizing the number of active systems when they are not strictly required. Key contributors include:

- ***Heating, cooling, and airflow optimization:*** Both the HV battery and drivetrain thermal management systems are designed for high efficiency, resulting in significantly lower energy consumption. And the prototype vehicle used for testing does not have an active compressor for air conditioning.
- ***Drivetrain auxiliary energy consumption:*** Approximately 30 W for Lightyear, compared to 100 W or more for typical industry solutions.
- ***Battery auxiliary energy consumption:*** Approximately 30 W for Lightyear, compared to 100 W or more for typical industry solutions.
- ***Infotainment, displays, and ambient lighting:*** Around 50 W for Lightyear, versus 200 W or more in conventional vehicles.

- ***ECUs and controllers:*** Roughly 30 W for Lightyear, compared to ~60 W for industry-standard architectures.
- ***Reduced always-on driver assistance systems:*** Fewer continuously active systems, such as self-driving cameras and related sensors, which are often kept permanently powered in other vehicles. Can easily consume 100+w in various conditions for other vehicles.

Overall, this low auxiliary consumption is not the result of a single optimization, but rather a system-level design philosophy that prioritizes energy efficiency across all subsystems.

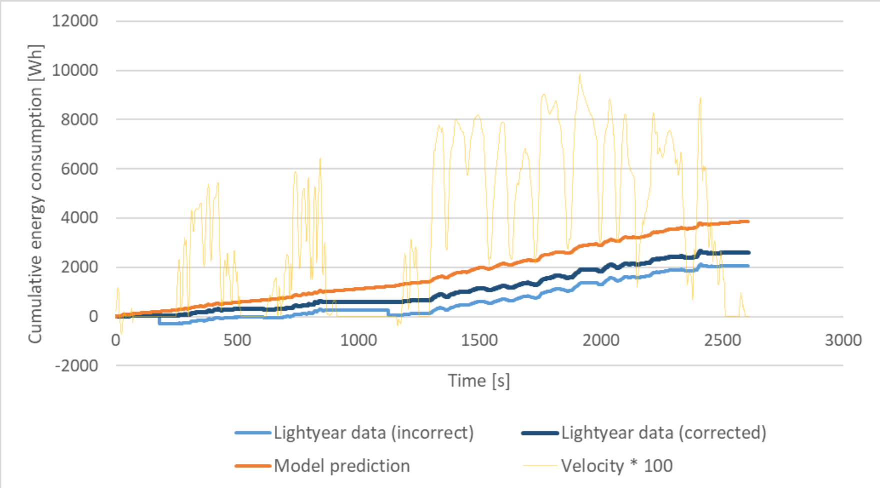


Figure 71: Test trip Lightyear 0 on 5 November, corrected for intermediate charging

When correcting for the idle consumption, for the two first tests (23 October and 28 November) the gap is further closed. If we look at Figure 72, it can be seen that the data starts with an idle period (during the first 350 seconds the vehicle drove only for 12 seconds). As visible in the graph, the model overestimation stems mostly from that period.

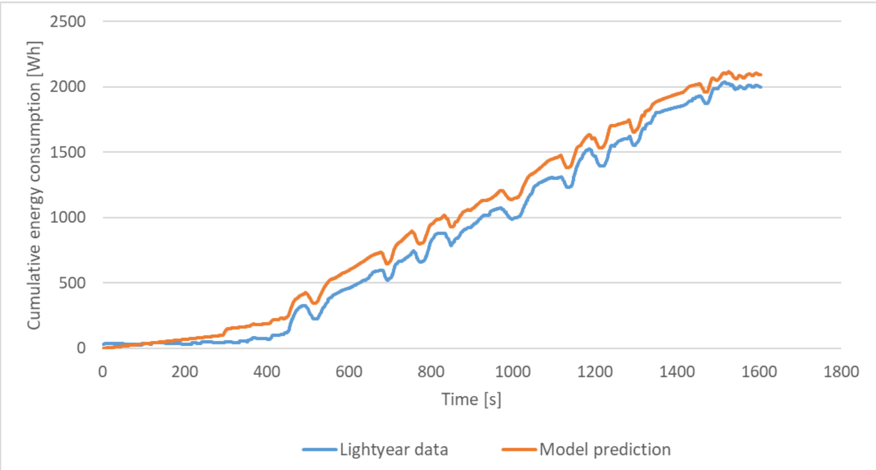


Figure 72: Test trip Lightyear 0 on 23 October 2024

A similar correction is needed for November 5th, which will reduce the gap between measurement and model further.

2.3.3. MEO model validation for a large van

Sono has provided energy consumption telemetry data of the electric Ford Transit van for the nine test drives done at the Ford test track, as described in paragraph 2.4.6. Each day had a fixed pattern; the variation is in the ambient temperature. The energy consumption data of the vehicle is completely independent from the VIPV system, except possibly for the additional weight of the installation. The specifications of the vehicle and some test conditions are included in Table 33.

Table 33: Vehicle specifications and test conditions

Property	Value	Comment
Brand and model	Ford E-Transit	
Size	L2H2	Large van, LV2x
Empty mass	2492 kg	
Width ex mirrors	2059 mm	
Height	2534 mm	Without payload
Air drag coefficient	known	Confidential
Gross vehicle weight	4250 kg	
Payload during the tests	125 kg	
Occupance during the tests	Two persons	
Battery capacity	67 kWh	Rated
Battery capacity during tests	60-62 kWh	
Airconditioning use during tests	on	

As listed in 2.4.6, test data included vehicle speed (from CAN bus data), GPS speed, high voltage current and voltage, low voltage current and voltage, ambient temperature.

On each test day, two main tests were done, each approximately 2 hours and 15 minutes and between 130 and 150 km (see Table 40). These tests, 18 in total, were converted into input files for the MEO energy consumption model, containing Time elapsed, vehicle speed, slope, payload, datetime and ambient temperature. The modelled results for the 18 tests exhibit an average energy consumption of 28.2 kWh/100 km. The actual (measured) energy consumption is 28.9 kWh/100 km, some 2.5% higher. The average deviation per trip is 4.4%. Figure 73 shows the individual results.

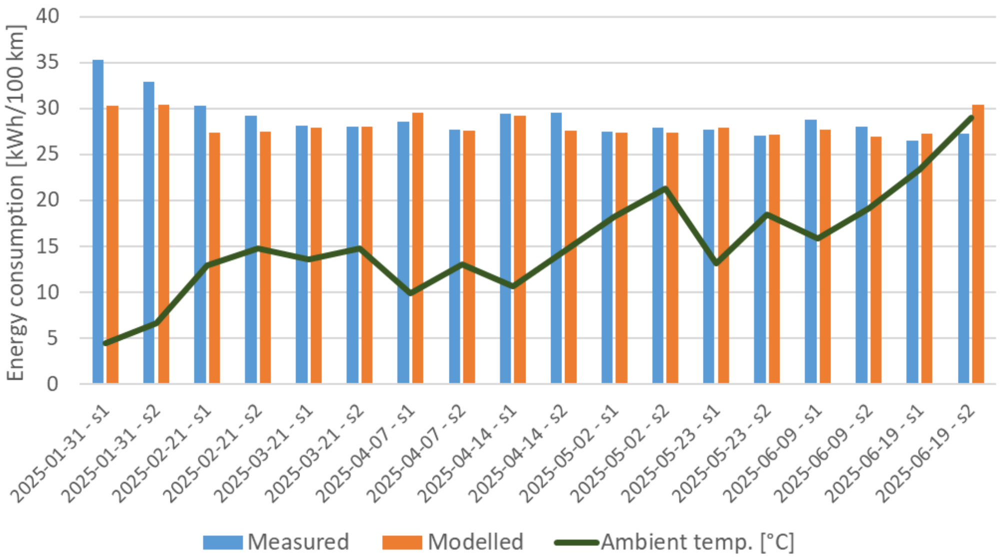


Figure 73: Comparison of test results for electric van

The model generally underestimates the energy consumption. This is especially true for the first, third and last trip. The ambient temperature was added to the graph, to check if the model underestimation is dependent on it. This is indeed the case, as shown in Figure 74. The vehicle has a PTC (positive-temperature-coefficient) heater, while the model assumes a heat pump. This can account for the underestimation at low temperatures. At high temperatures, the model seems to overestimate the consumption however. Possible reasons are: the modelled energy consumption of the air conditioning is too high, the model overestimates the consumption of this vehicle in general (although not likely, judging from the other data points), and/or the vehicle's propulsion efficiency is affected by temperature more than envisaged in the model.

The result of an average deviation of 4.4% is acceptable. However, the model should be improved to allow for PTC heater configuration, and the propulsion efficiency dependency of ambient / battery temperature should be assessed.

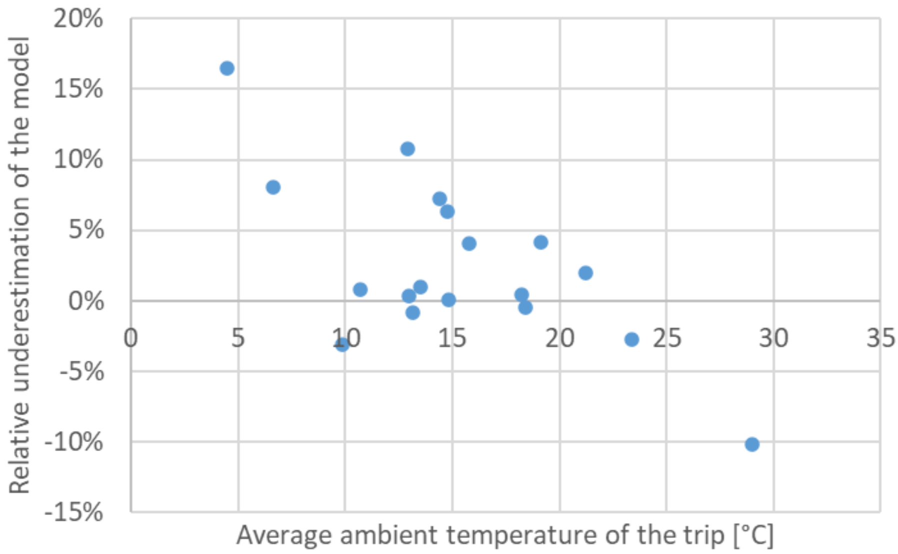


Figure 74: Underestimation of the model against the ambient temperature

2.4 Case studies from the project

This paragraph presents a series of real-world case studies that demonstrate the performance and potential of vehicle-integrated photovoltaics (VIPV) across different vehicle types and operational contexts. The analysis includes:

- **Lightyear 0 Passenger Car:** Showcasing how an ultra-efficient EV with integrated solar panels reduces grid dependency and charging frequency, validated through extended measurement campaigns under varied conditions.
- **Peugeot Boxer Luton Van:** Evaluating solar energy potential on multiple vehicle surfaces and the influence of driving patterns, orientation, and parking on solar yield for urban and regional delivery operations.
- **Long-Haul Distribution Trucks:** Assessing geographic and seasonal variations in solar harvest for heavy-duty freight vehicles, highlighting the significant contribution of large roof and side areas to energy generation.

- **Electric Food Delivery Truck:** Demonstrating how onboard solar systems consistently supply a meaningful share of daily energy needs in urban delivery profiles, reducing traction battery load and improving operational efficiency.
- **Urban Bus Fleet (Nitra):** Quantifying solar contribution for municipal transport applications, emphasizing the role of route characteristics and parking conditions in determining solar yield.
- **Electric Van (Sono Motors):** Reporting on controlled test drives simulating last-mile delivery routes, showing measurable benefits of onboard PV in extending range and reducing charging time, and informing future system optimizations.

Together, these case studies confirm that VIPV can deliver tangible operational, environmental, and infrastructure benefits across passenger, commercial, and public transport vehicles. They provide critical insights into real-world performance, validate simulation models, and highlight opportunities for scaling solar integration in diverse mobility applications.

Section 2.3 demonstrated that the MEO vehicle energy consumption model reproduces measured real-world energy use with acceptable accuracy across passenger cars, vans, and heavy-duty vehicles, while also identifying specific sensitivities related to auxiliary loads, thermal management, and temperature effects. Building on this validated modelling framework, Section 2.4 presents a set of project case studies that illustrate how VIPV performs in real operational contexts, combining measured data and model outputs to assess practical implications for different vehicle types and use cases.

2.4.1. Lightyear: Lightyear 0 case study

Methodology & results of energy measurement in passenger vehicle

The Lightyear 0 is being used to measure real-world performance and efficiency across various components of an electric vehicle while demonstrating the impact of high-efficiency components and integrated solar panels on factors as the driving energy consumption, grid dependency, and charging frequency. With its 5.05m² onboard solar array, the vehicle provides a unique opportunity to directly correlate energy efficiency with real-world solar yield. These measurements provide insights into energy consumption, solar yield, and overall vehicle efficiency, and helping to validate simulations and the results of the SolarMoves project. The following paragraph provides an overview of the Lightyear 0's architecture, the measurement setup, the tested use cases, and the performance results gathered so far.

Short intro Lightyear Zero

The Lightyear 0 is a limited-production vehicle designed to showcase the potential of efficiency and integrated solar photovoltaics. Every aspect of the vehicle's design—including aerodynamics, power electronics, drivetrain, and thermal management—has been optimized to minimize energy consumption and maximize the usability of solar power. See the overall architecture of the Lightyear 0 in Figure 75.

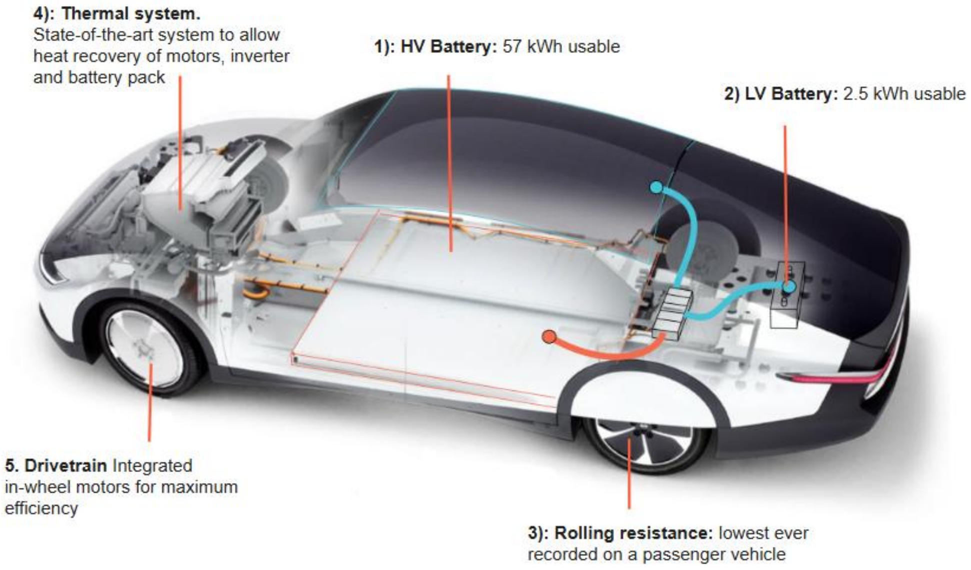


Figure 75: Overview of architecture of the Lightyear 0 test vehicle

For details on the solar architecture and overall performance, refer to Figure 75, which highlights the system's key specifications. The vehicle is equipped with 4.87m² of active solar area, capable of a peak output power of 1.01 kW under STC conditions. This integrated solar system, Figure 76, plays a key role in reducing the vehicle's reliance on external charging.

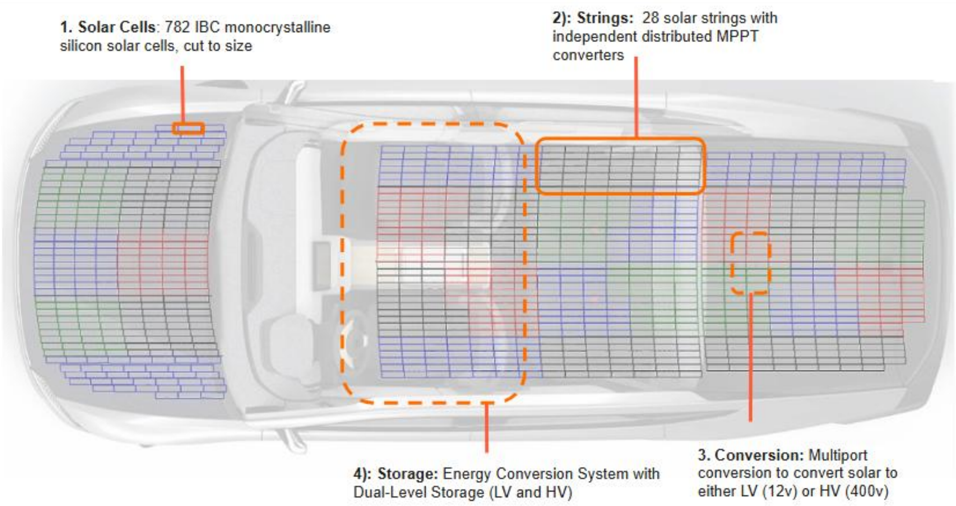


Figure 76: Overview of the solar system of the Lightyear 0 test vehicle.

Measurement setup

For this measurement campaign, an adjusted vehicle setup has been implemented to address specific testing requirements and limitations. Under normal operating conditions, the Lightyear 0 is equipped with a Low Voltage (LV) battery and a High Voltage (HV) battery, with solar energy from the Distributed Maximum Power Point Trackers (DMPPTs) feeding directly into the LV battery, or into the HV battery via the bidirectional DC/DC converter.

To isolate solar yield measurements from overall vehicle consumption, an additional battery has been installed. This allows the solar system to operate independently and gives the possibility of completely separating the solar yield and driving energy measurement.

Additionally, this extra battery powers extensive logging equipment, including a laptop running 24/7 in the vehicle, which would otherwise introduce an additional parasitic load. By measuring solar power and energy before it reaches the vehicle batteries, we directly measure how much solar energy would have been stored under normal operation, excluding logging-related energy consumption.

The following schematic illustrates the energy flows in the vehicle, and how the measurement equipment is connected:

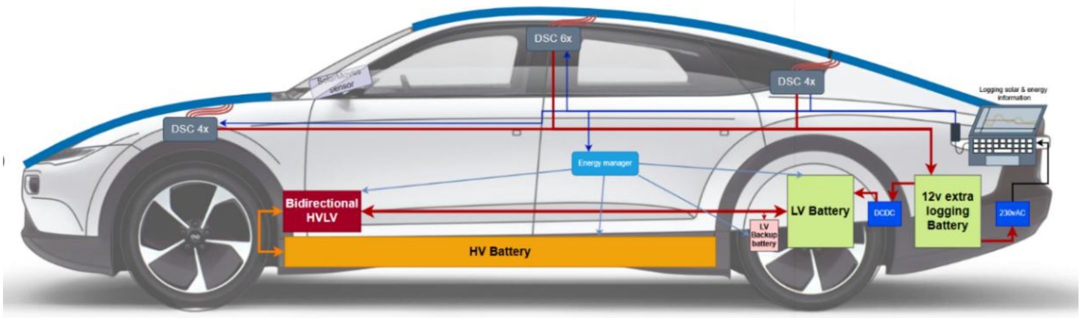


Figure 77: An overview of the energy measurements and equipment in the Lightyear 0 test vehicle

Additionally, see Figure 78 for a schematic overview of the energy measurements and at which part of the system the energy yield or usage is measured.

A) Measured solar energy from the onboard solar setup, capturing real-time solar power generation.
B) Switch to connect/disconnect the extra 12V battery, allowing for isolated solar energy measurements without influencing the car's energy flow.
C) LV battery energy measurements (2.5 kWh capacity), recording the power supplied to all 12V auxiliaries.
D) HV battery energy measurements (57 kWh capacity), tracking energy flow to HV components, including HVAC and the drivetrain.
E) Logging equipment powered from an extra battery, ensuring that data collection does not affect the vehicle’s efficiency measurements.

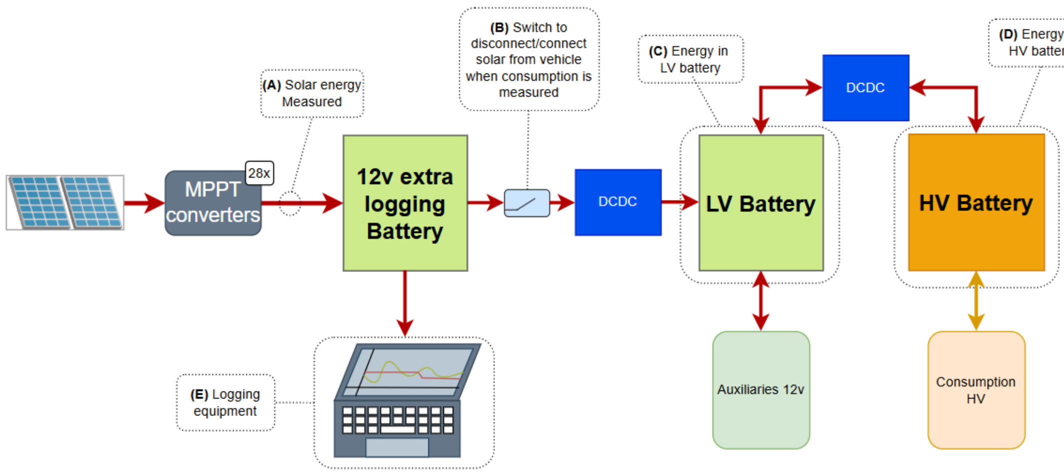
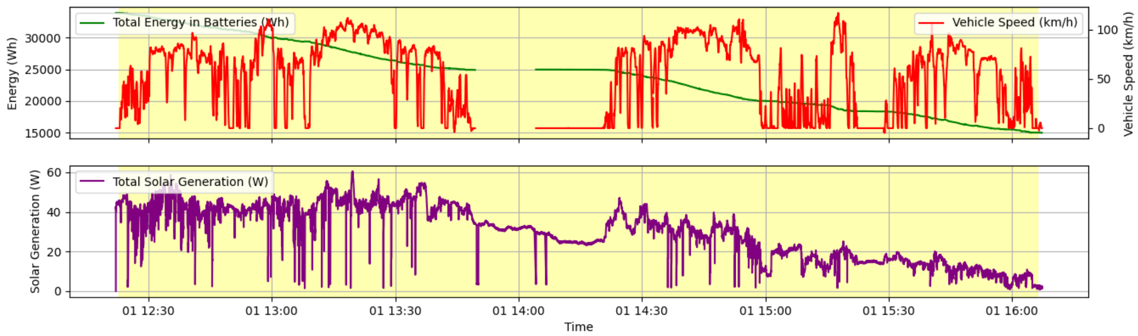


Figure 78: A schematic overview of the measuring setup of the lightyear test vehicle

Results

To highlight how the efficiency and solar yield are measured, two datasets have been selected—each representing different driving conditions and solar exposure levels. These datasets are compared against simulated efficiency values for the Lightyear 0 to assess real-world performance.

The first dataset (Figure 79) represents a longer trip with varied speeds, where solar generation was minimal due to cloud cover and seasonal low irradiance. Since PV generation was only measured during the drive, additional solar input from the stationary period was not accounted for.



Total Kilometers Driven(Selected): 178.96 km
Total Energy Used (Selected): (12:22:51 to 16:06:09): 18884.60 Wh
Energy Consumption (Selected): 105.53 Wh/km
Solar Yield (Selected): 110.89 Wh
Solar Yield (Entire Log): 111.85 Wh
Consumption w/ Solar (Selected): 104.91 Wh/km
Consumption w/ Solar (Entire Log): 104.90 Wh/km
Total Energy Charged from Grid: 0.00 Wh

Figure 79: Energy profile of 180 km drive with 45-minute break, fully clouded day, Driver + 1 passenger (07 November 2024)

The second dataset (Figure 80) reflects a typical daily commute, where the vehicle benefits from solar charging while stationary. The solar contribution (27% in the Netherlands in February) to the total energy consumed already starts to demonstrate the potential impact of vehicle-integrated solar (VIS) in reducing grid dependency and extending driving range. The total distance driven is 61.61km in this case, separated by 7.5h of the car standing outside in the sun. The total solar yield over the day was 1835Wh generated by the vehicle, while the overall irradiance of a nearby weather station shows that the solar irradiance was 2500Wh/m2 for that specific day (Feb 26th).

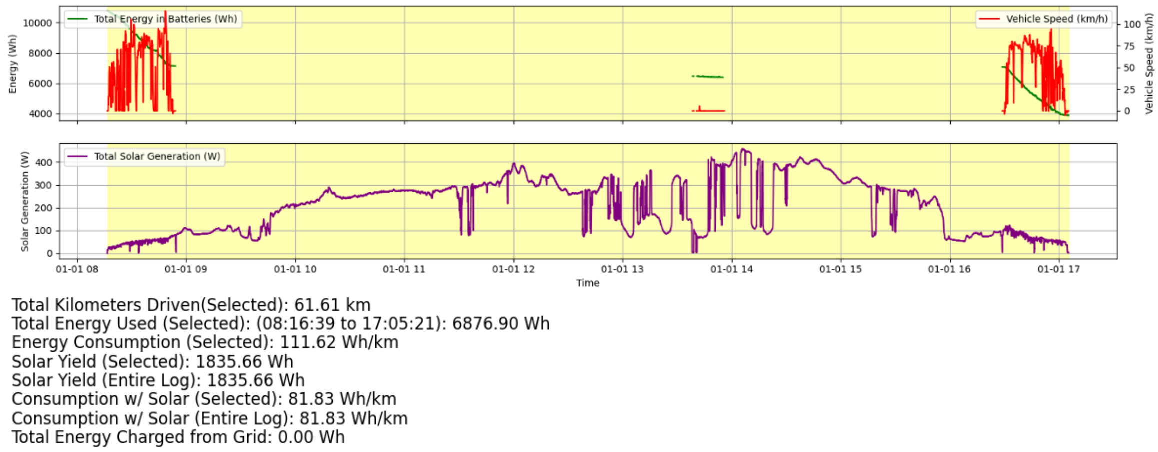


Figure 80: 61.31km drive with a full day in the sun in February

In summary, some of the measurements are shown in the table below with a total distance driven, the measured vehicle efficiency, the measured solar yield, solar irradiance data and the solar kilometres charged. Specifically for the solar yield generated, most tests were not covering the complete timeframe of daylight, and one (out of the 28) of the Lightyear solar string groups is not up and running, which could result in the panel specifications of 5.05m2 and 1.05kW peak, instead of the current 4.87m2 and 1.01kW peak.

Table 34: Highlighting efficiency and solar charged range over various test days for Lightyear 0

Month	Example Use case	Solar Irradiance (Wh / m2) over full day (from weather station)	Vehicle solar yield measured (Wh)	Vehicle efficiency measured (Wh/km)	Solar KM charged
Oct	Day outside, 20min noon drive	1750	1230	104	12
Nov	Day outside, 20min noon drive	2170	1600	98	16
Dec	Longer mid-day drive, parked inside	280	105	106	1
Feb	Commute roundtrip with outdoor parking	2500	1835	111	17

To build on the preliminary findings, the project carried out an extended measurement campaign in summer and autumn (most measurements were done between 1st of August, and 15th of Sept). The goal was to capture real-world VIPV performance during the more favourable solar conditions of the year compared to the second interim report, providing a data set for both validation and insight into maximum potential benefits. Over the course of this campaign, the Lightyear 0 test vehicle was operated daily in mixed driving and parking conditions while continuously logging energy metrics. The campaign spanned 20 testing days, during which the car was driven 1,186 km in total, in a mix of daily commutes and day trips. By covering a broad range of clear and partly cloudy days, the tests yielded a robust & realistic dataset on how much solar energy a passenger EV can harness under these seasonal conditions. This measurement campaign with the Lightyear 0 was fully conducted in the Netherlands.

The measurements from the extended campaign shows the significant impact of the solar yield, especially on a highly efficient vehicle like the Lightyear 0. Over the 20 testing days (randomly picked, not based on best weather days), the solar contribution shows an average of 23.7km per day, with the best day generated 46.05 km's, and the worst day generated 11 km's. In total there where 4 out of 20 days, where the solar generation was more than the distance driven by the vehicle. Table 35 (below) summarizes the key performance metrics recorded.

Table 35: key performance metrics recorded for the Lightyear 0 over the 20-day period

Metric	Total (20 Days)	Average Per Day	Description/Notes
Total Distance Driven	1,186 km	59.3 km	Mixed usage (commute & long range).
Total Electrical Energy Consumed	111.3 kWh	5.56 kWh	Gross energy consumed by HV and LV systems combined.
Solar Energy Generated	49.3 kWh	2.47 kWh	Direct output from onboard PV system.
Equivalent "Solar Driving" Range	473 km	23.7 km	$\frac{(Solar\ energy\ generated\ \cdot\ 0.9)}{Gross\ energy\ consumption}$
Gross Energy Consumption	94 Wh/km	—	$\frac{Total\ Energy\ Consumed}{Total\ km's\ driven}$
Net Energy Consumption	56 Wh/km	—	$\frac{Total\ Energy - (Solar\ Energy \cdot 0.9)}{Total\ km's\ driven}$
Solar Energy Contribution	39.8%	—	Percentage of Solar driving range compared to the total driven distance.

**Note: A 0.90 integration efficiency factor is applied to account for conversion losses from the PV system to the High Voltage (HV) battery.*

In Figure 81 all the individual testing days are plotted, with both the total distance driven, and energy generated on the same day. The average of both values is plotted in dotted lines.

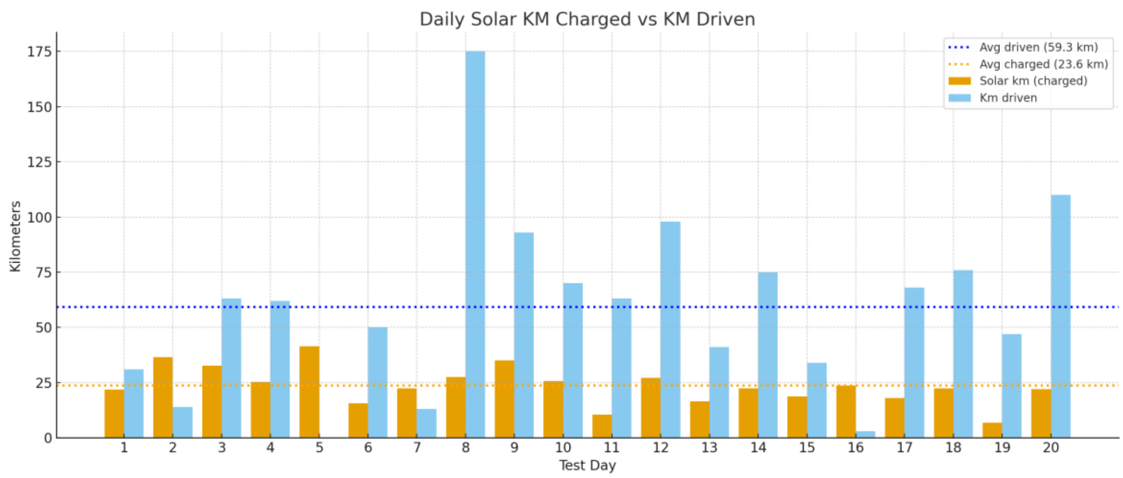


Figure 81: Overview of the 20 testing days comparing the KM's driven with the Energy generated

As an example of how the data is processed and how it looks, a detailed breakdown of Day 8 is provided in Appendix K. This includes the speed profile, energy consumption, and solar generation over an afternoon with a 163 km trip.

Contextual Impact of Solar Contribution from the Summer Campaign results

This campaign was executed under a high-usage driving profile of 59.3 km/day, equivalent to more than 21,600 km/year—significantly above the Dutch and EU averages of approximately 13,000 km/year. Even so, solar energy provided roughly 40% of all driven km's during the campaign, demonstrating robust VIPV performance even under demanding daily usage, and highlighting the reduction of energy demand from the grid.

Additionally, this campaign was conducted in the Netherlands, under relatively modest solar irradiance conditions. This provides a conservative and therefore robust reference point for understanding VIPV performance across Europe. Across randomly selected days—including those with mixed weather conditions—the vehicle consistently produced 1 to 3 kWh/day, and these typical days largely determined the overall average output. On the campaign's best day, however, the car produced 46.05 km worth of solar energy, highlighting the upper bound of daily contribution in Dutch summer conditions. In more southern European climates, where summer irradiance is significantly higher, comparable "good days" could consistently exceed this value, offering even greater reductions in charging frequency.

In summary, for typical drivers with lower yearly mileage and/or in more southern European climates, the relative share of solar kilometres would be significantly higher—along with the associated user and infrastructure benefits. In practice, this means that an average driver would experience an even larger contribution from solar energy and require less energy from the grid.

Conclusion of the Lightyear 0 energy management campaign.

Across the Lightyear 0 campaigns, real-world measurements confirm that an efficient EV like the Lightyear 0 can drive with a gross vehicle consumption of 0.09–0.11 kWh/km, and that it benefits significantly from an onboard solar system. In the winter tests in the Netherlands from the Second Interim Report, the PV roof still harvested roughly 0.1–1.8 kWh of solar energy per day, depending on weather and parking; on a clear February day the car generated 1.8 kWh from the roof, enough to cover about 17 km without any grid energy.

Under summer–autumn conditions, the extended campaign recorded 49.3 kWh of solar yield over 20 days, averaging 2.5 kWh/day, while the car drove 1,186 km and used 111.3 kWh in total during this test period. The onboard solar panels enabled about 473 km of "solar driving" and, after conversion losses, replaced roughly 44 kWh that would otherwise have been charged from the grid—meaning only around 67 kWh of external electricity was needed for the entire period to cover the 1186 km's. Together, the winter and summer results show that even under less-ideal weather conditions, and in a location like the Netherlands, onboard solar can contribute a substantial share of total energy use. This reduces both the frequency and size of plug-in charges and confirms that VIPV on passenger cars can meaningfully ease dependence on public and home charging infrastructure.

2.4.2. IM Efficiency: Case study Peugeot Boxer Luton

The Peugeot Boxer Luton was selected for an in-depth analysis. Data is being recorded since March 2024 and still running. For analysis we use the data over a six-month period from March 2024 to September 2024. Three solar sensors were installed on this vehicle using a designated base plate as shown in Figure 82.

- Top Sensor**:** Mounted at a height of 2.8 m from the ground
- Left and Right Sensors**:** Mounted at 2 m from the ground

Figure 82: Peugeot Boxer Luton and base plate

Driving Profile and monthly solar energy production

The driving profile was recorded by the sensor to correlate with irradiance data as shown in Figure 83. This vehicle mostly has a driving profile around Netherlands, Belgium and Germany.

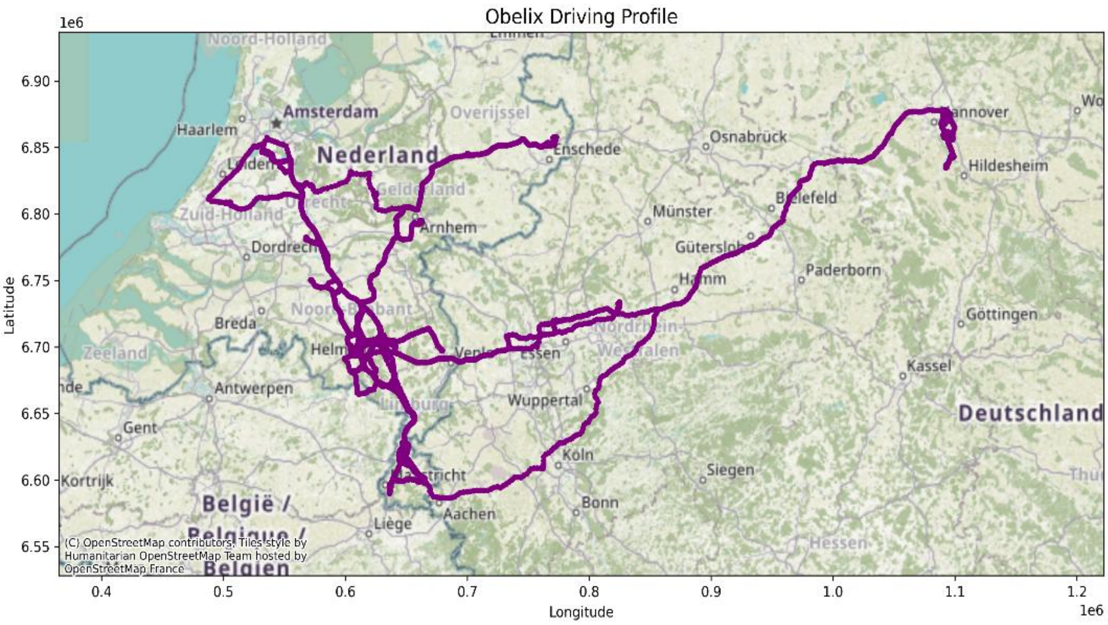


Figure 83: Driving profile for the Peugeot Boxer Luton

The irradiance data acquired from the sensor in W/m² is sampled per minute time stamp and the total solar energy production in Wh/m² is calculated and compared between the top, left and right sensor respectively.

From Figure 84 it is evident that the total energy produced from the top sensor is equal to approximately the sum of energy produced from both sides.

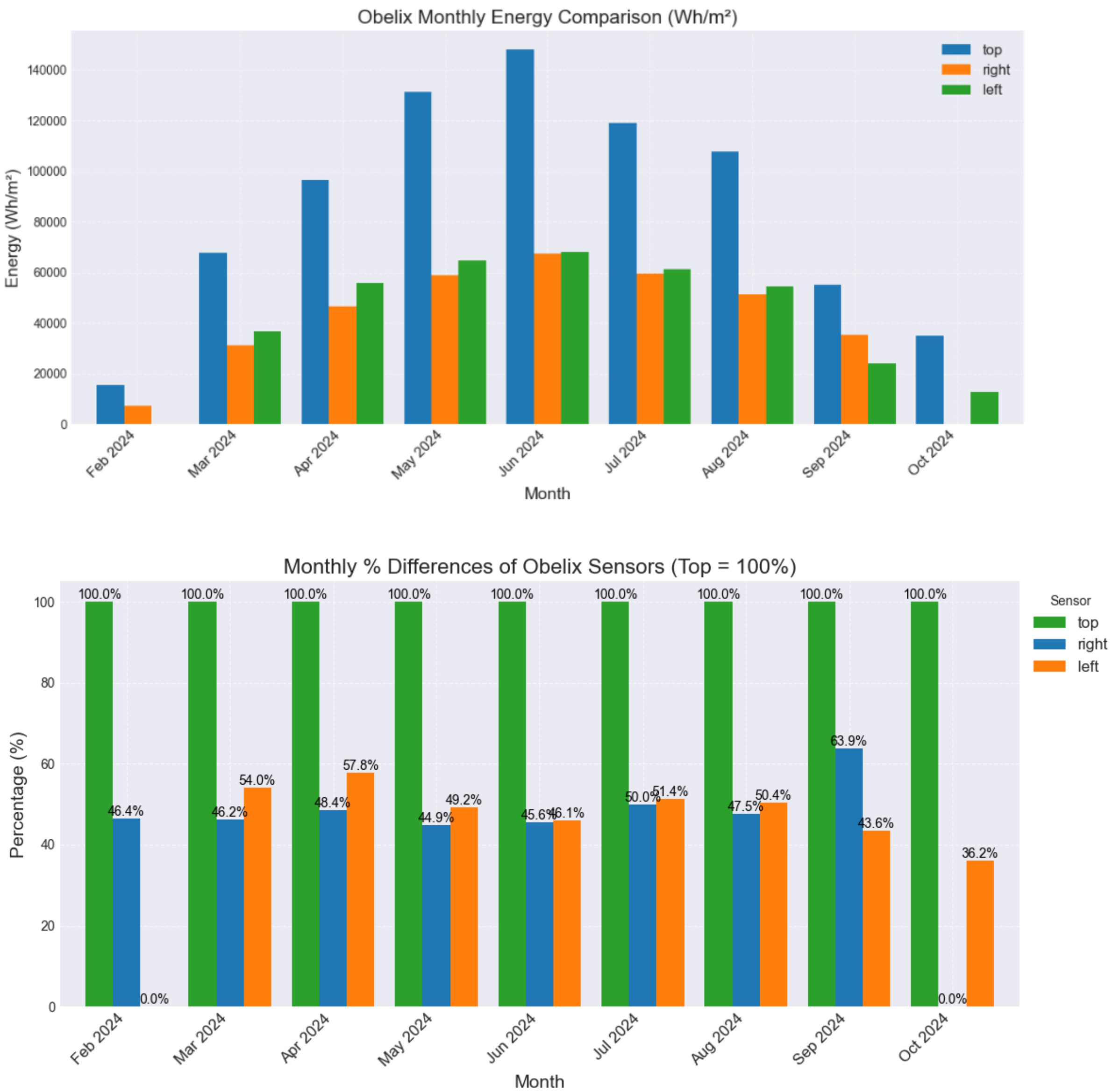


Figure 84: Monthly energy consumption analysis for the Peugeot Boxer Luton

Looking at the per day solar energy that could be generated from the collected irradiance data, we can visualize a box plot as shown in Figure 85. On an average the top sensor is capable of producing ~2800 Wh/m² while the right sensor can produce ~1200 Wh/m² and left ~1400Wh/m².

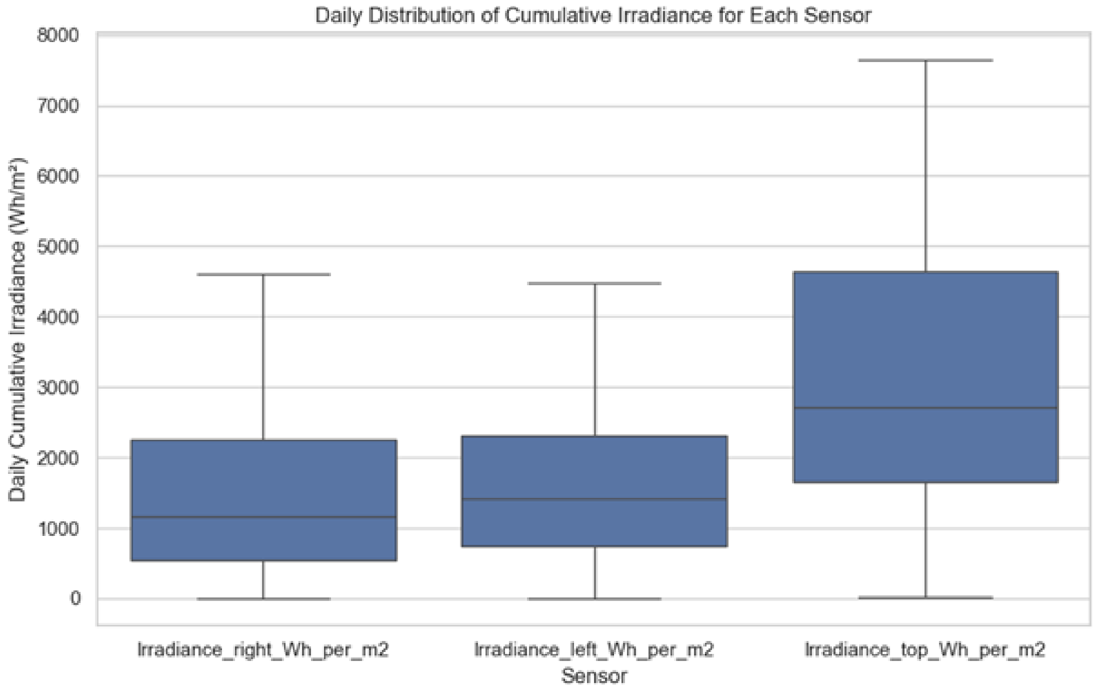


Figure 85: Box plot per day solar energy

A maximum of 7505.4 Wh/m², 4213 Wh/m² and 3728.4 Wh/m² can be generated from the top, right and left sensors respectively on a best day which in this case was on 09/06/2024. For this particular vehicle archetype, a top area of 8 m² and a side area of around 4 m² can be covered with solar panels. This amounts to a total of 60 kWh from top, 17 kWh from right and 15 kWh from the left side solar panels of the vehicle. The total irradiance distributed over the day is shown in Figure 86.

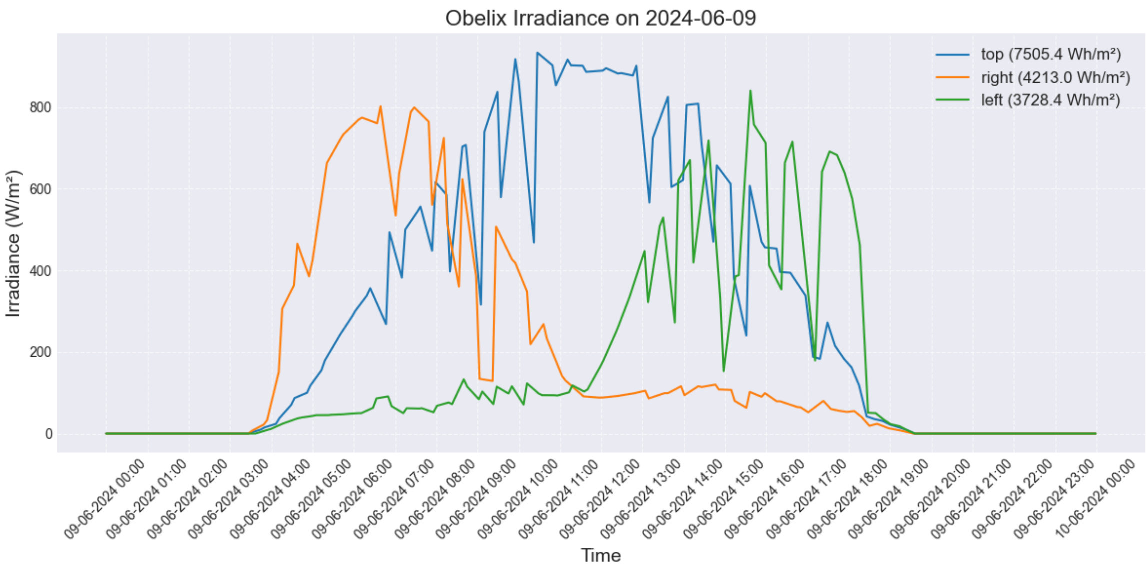


Figure 86: Best day 09/06/2024 Peugeot Boxer Luton

Analysis - Sample trip to Hannover

The vehicle has driven on a trip to Hannover from the Netherlands on 15/09/2024 and returned on 22/09/2024, as shown in Figure 87.

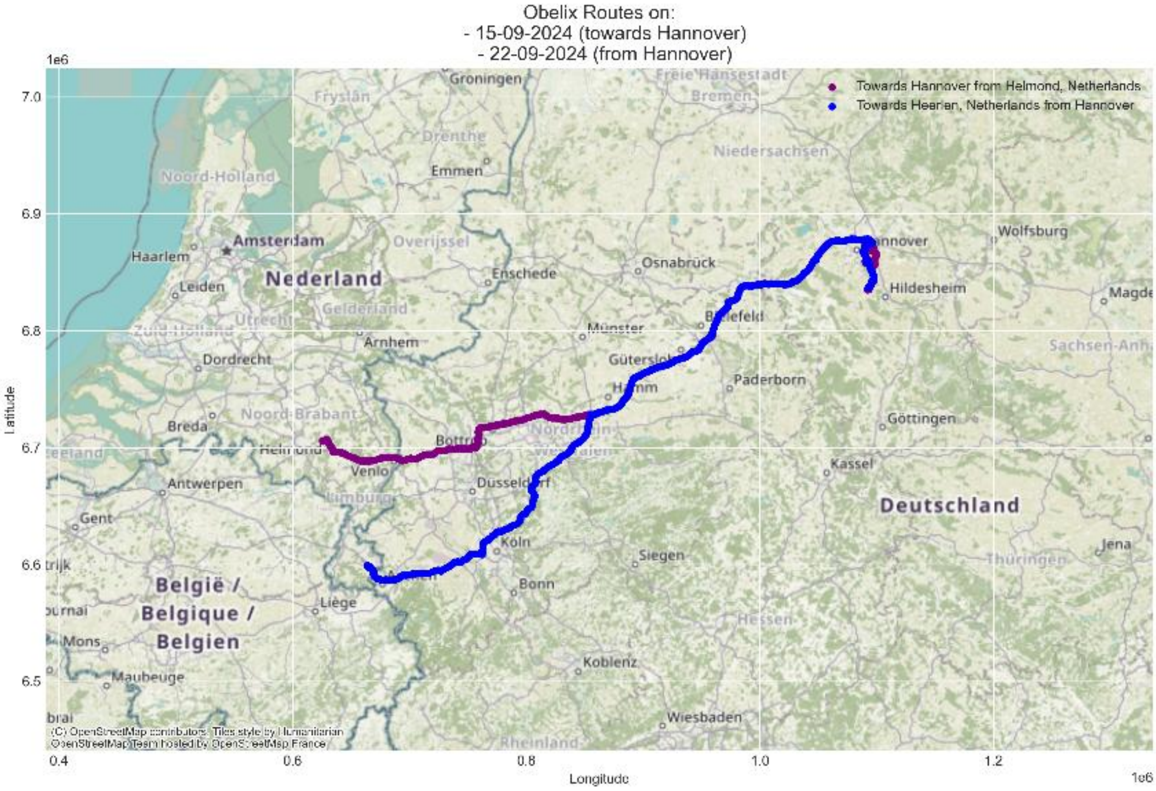


Figure 87: Example trip to Hannover from the Netherlands and back

While going towards Hannover the vehicle is driving eastwards which is towards the rising horizon of sun and the left sensor is facing north, receiving less radiance than the south facing sensor. And upon returning it is on the other way round. Thus, the travel direction has a direct impact on the solar energy production from the sensors placed on the sides as shown in Table 36. Figure 88 and Figure 89 visualizes the irradiance vs time of the day during the trip towards Hannover and during the return trip.

Table 36: Vehicle orientation and energy production

Trip Date	Direction of travel	Top Sensor (Wh/m²)	Left Sensor (Wh/m²)	Right Sensor (Wh/m²)
15-09-2024	Eastward	2682.8	954.9	1807.8
22-09-2024	Westward	3696.5	4484.1	980.9

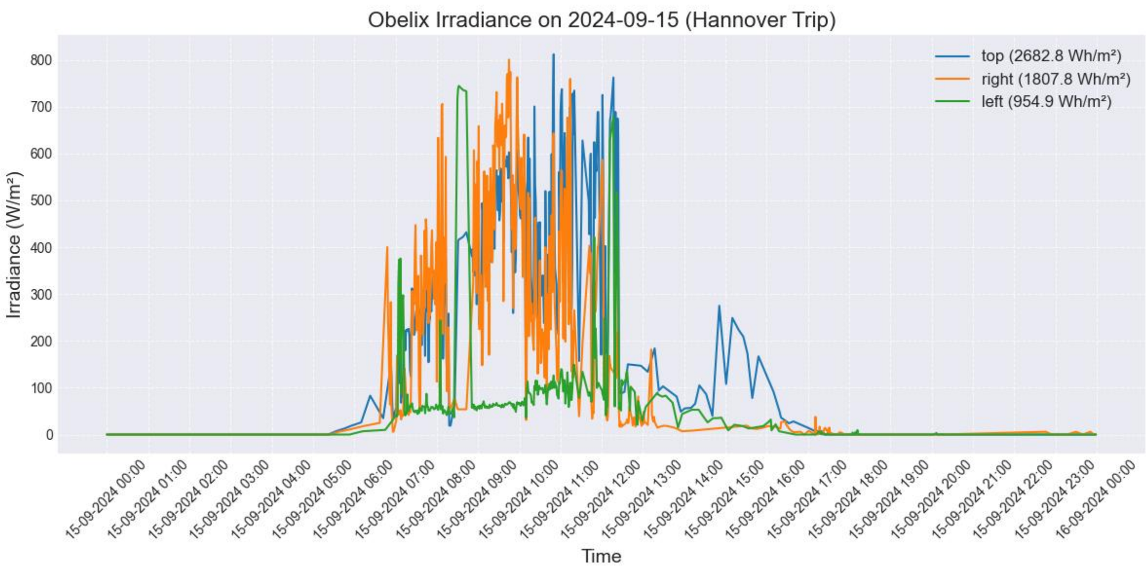


Figure 88: Towards East to Hannover

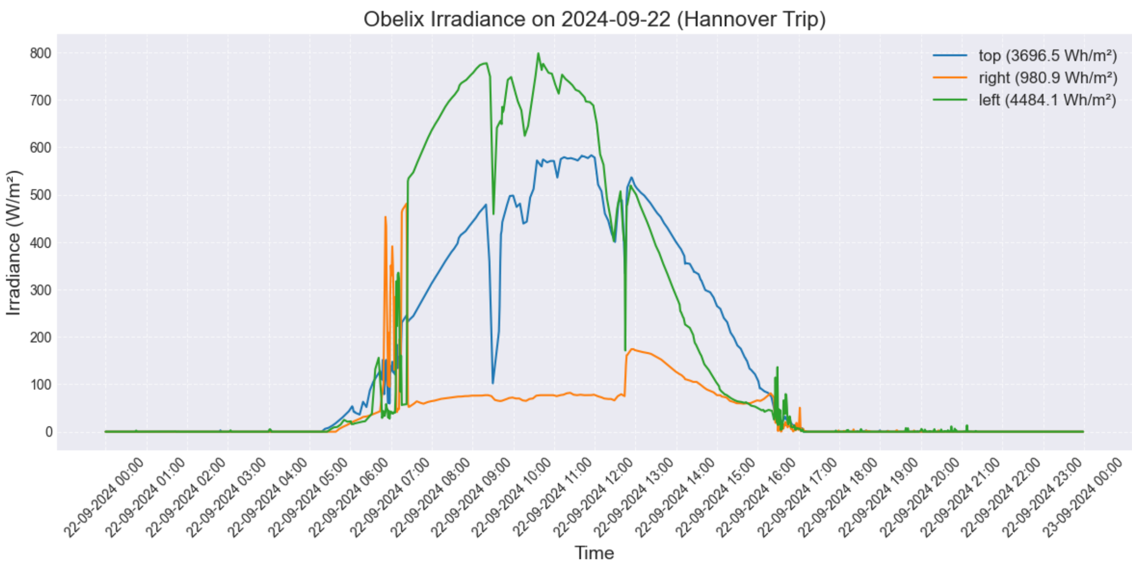


Figure 89: Towards west to the Netherlands

2.4.3. IM Efficiency: Case study long-haul distribution truck

Three long haul distribution trucks were each equipped with a single horizontal irradiance sensor mounted on the cabin roof, so all measurements in this study represent the potential yield of a flat, roof integrated PV module that rotates with the vehicle heading but always remains horizontal. Over the period from late August (25/08/2025) to mid-November 2025 (15/11/2025), the three trucks collectively covered latitudes from about 40°N (northern Spain) to 60°N (southern Scandinavia) and longitudes from roughly 6°W (Eastern Ireland) to 21°E (Poland), thereby covering a wide range of European climate zones as shown in Figure 90.

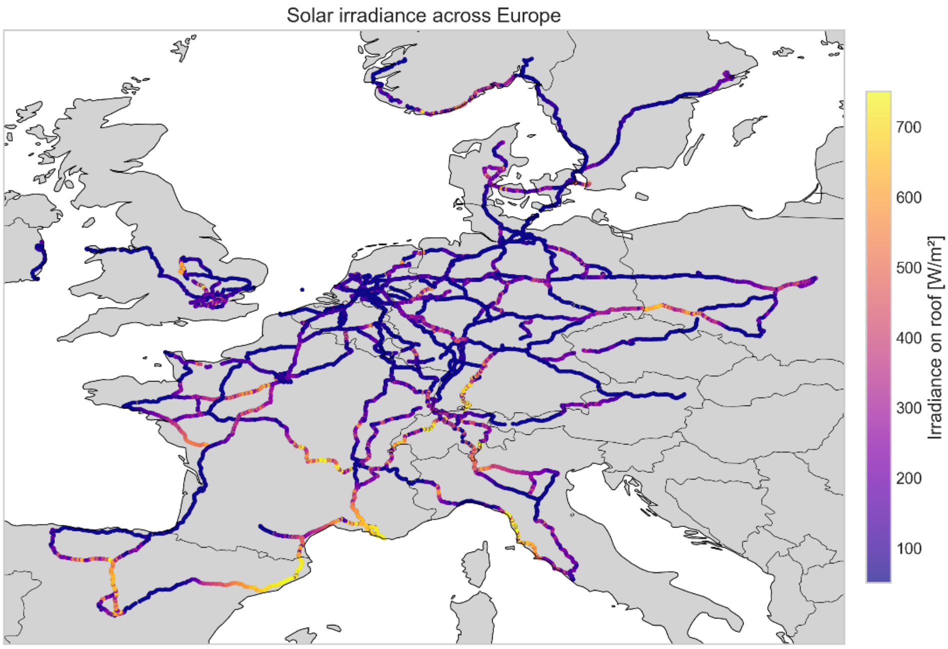


Figure 90: Combined irradiance map for 3 long haul distribution trucks travelling over Europe

To investigate geographic effects, all data collected were classified into three latitude bands that approximate Southern Europe (lat<45°N), Central Europe (lat 45–55°N) and Northern Europe (lat>55°N) consistent with European PV studies as shown in Figure 91.

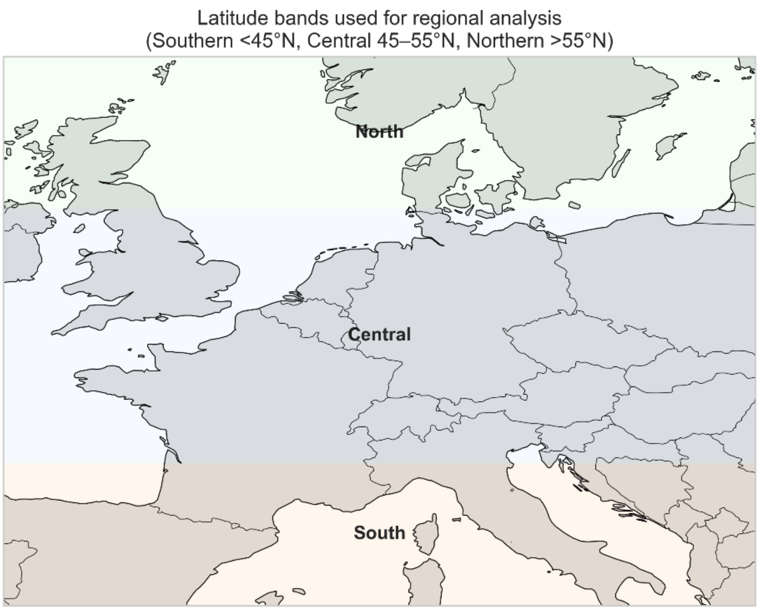


Figure 91: Latitude bands used for regional analysis of the data

The box plot of daily solar energy in Figure 92 shows that truck 1 experienced the widest spread of daily energy yield, with many days exceeding 2000 Wh/m², reflecting that this vehicle spent substantial time in late summer conditions and in southern latitudes. trucks 2 and 3 have tighter interquartile ranges (orange and green region of the bar plot), which is consistent with their operation mainly in autumn and at northern regions where day length and typical irradiance are lower. The outlier points above high value for trucks 2 and 3 correspond to a small number of very clear days, underlining that even in autumn a truck roof can harvest substantial energy when weather and routing align favourably.

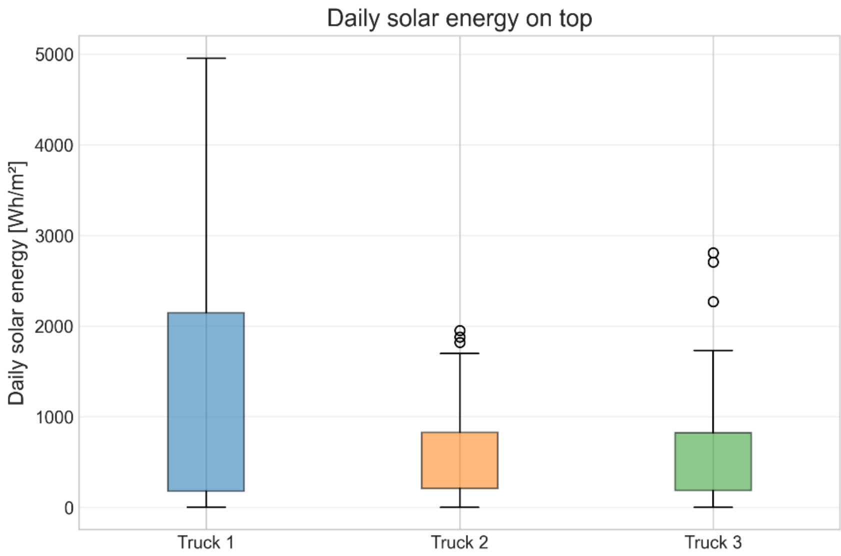


Figure 92: Box plot of daily solar energy recorded by all three trucks

The regional breakdown in Figure 93 reveals how geography and season together determine total solar harvest. Despite recording similar operating hours (approximately 450 hours) in the central European region, Truck 1 accumulated nearly 67 kWh/m² , almost double what Trucks 2 and 3 collected across this region. The difference demonstrates that solar yield from VIPV is fundamentally shaped by 'when' and 'where' the vehicle operates. Nevertheless, the data confirms that top-mounted solar panels on commercial vehicles is a reliable energy source across diverse European conditions, with the total harvest scaling predictably with regional irradiance and seasonal timing.

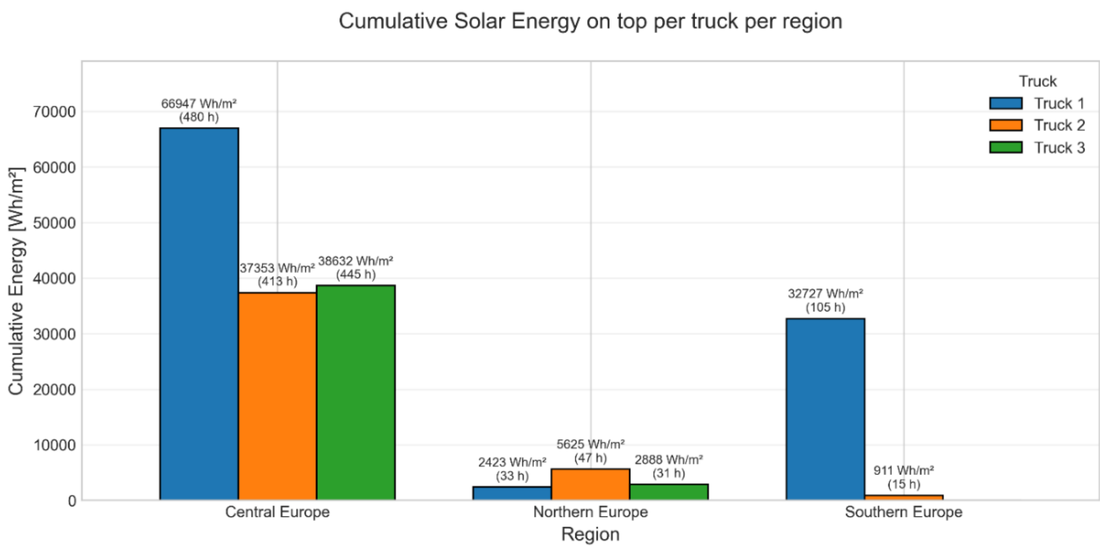


Figure 93: Cumulative energy recorded at different regions of Europe

June irradiance profile for long-haul trucks

From the data measured with the sensors during the measurement period which mostly comprises of autumn months, the irradiance profile of the same long haul trucks were computed for a summer month to validate the scenario of solar energy production during the month of June. The long term monthly average global horizontal irradiance for the Netherlands was obtained from the PVGIS SARAH database (EU JRC), which gives October GHI of roughly 70–80 kWh/m²/month (≈2,4 kWh/m²/day) and June GHI of about 165–180 kWh/m²/month (≈5,5 kWh/m²/day) for the Netherlands. This gives a valid factor to compare a best day in autumn with a day in summer for the trucks as shown in Figure 94 and the irradiance profile as shown in Figure 95.

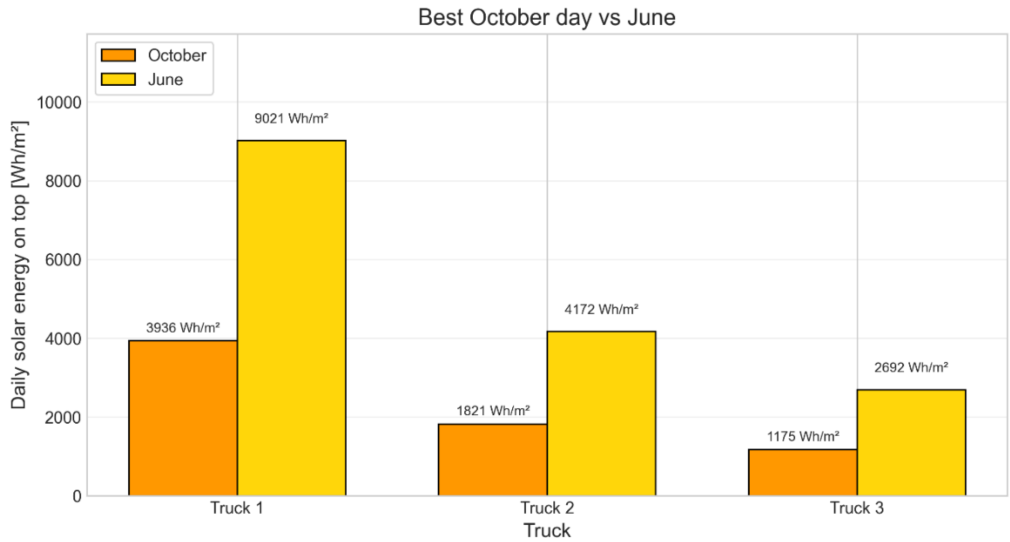


Figure 94: Daily solar energy on top of the trucks, shown for the best day in October and June

The bar plot in Figure 94 shows the solar irradiation energy in June can be almost more than twice as much as the October bars, which is consistent with the global irradiance in north-west Europe. Truck 1 reaches its highest value of around 9 kWh/m²/day indicating that the top of trailers in long-haul vehicles could be highly productive and capable of delivering several kWh taking into account that there is more than 30 m² of area available on top of the trailer. The irradiance profile in Figure 95 shows the route timing, driving pattern and dynamic shading that can be involved in different long-haul commercial vehicles.

Figure 96 quantifies the total solar energy that could be actually generated from the solar irradiation when the solar panels are also deployed on the top as well as the two vertical sides of a trailer body. Assuming a 30 m² on the top and roughly 60 m² on both sides of the body, with each side receiving an average of 50% of the top, meaning for example Truck 1 could actually generate 18 kWh/m²/day. When translated, the absolute energy corresponds to approximately 270 kWh/day only on the top, and about 540 kWh/day from all three surfaces for Truck 1. And similarly reaching up to 250 kWh/day and 160 kWh/day for Trucks 2 and 3 respectively. These magnitudes demonstrate that a long haul truck-trailer offers a very large and effective solar collection area, by utilizing both horizontal and vertical surfaces, vehicle integrated PV can supply a substantial amount of the electrical energy needed for the truck-trailer combination and can make a meaningful contribution to the traction energy especially during high irradiance/summer operation.

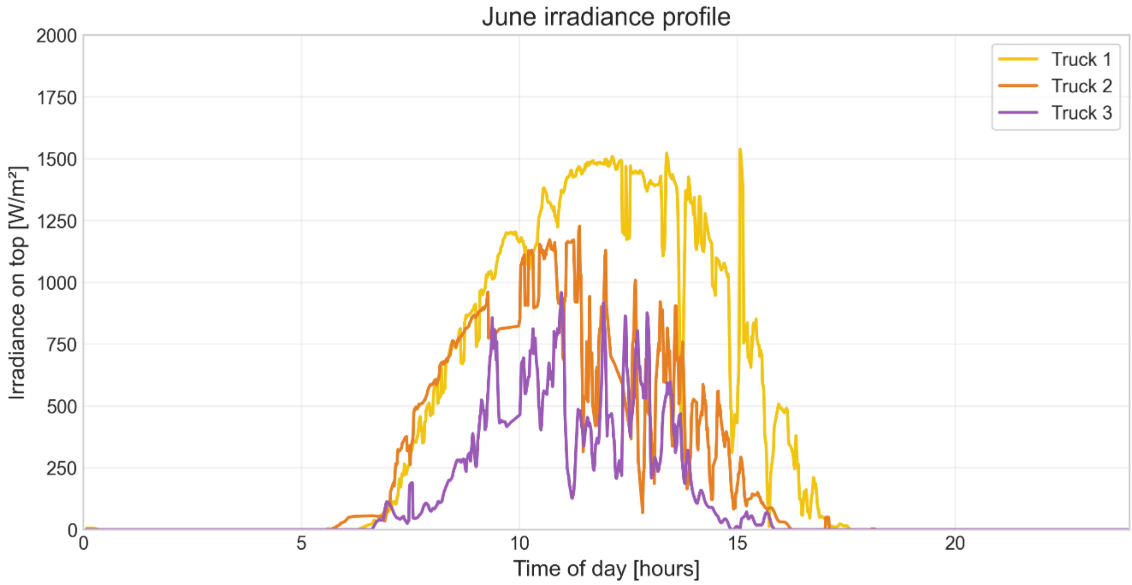


Figure 95: Estimated June solar irradiance profile per truck

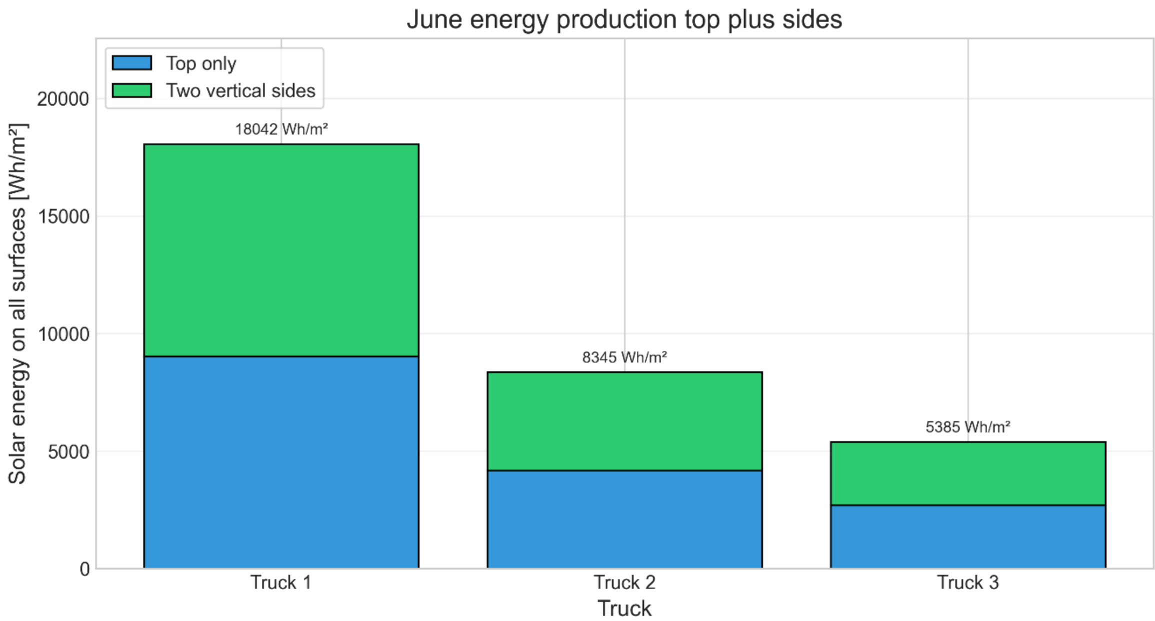


Figure 96: Total solar energy estimation from top and sides in June

2.4.4. IM Efficiency: Case study Electric food delivery truck

The local food distribution truck in this study is an electric rigid truck equipped with IM Efficiency's SolarOnTop (SoT) system as shown in Figure 97 which has flexible PV modules on the roof, an energy management system and a dedicated lithium buffer battery that interfaces with the vehicle's onboard electrical system. This architecture allows SoT to capture solar energy directly on the roof and feed it into consumers, thereby reducing the load on the main traction battery and extending the daily operating range.

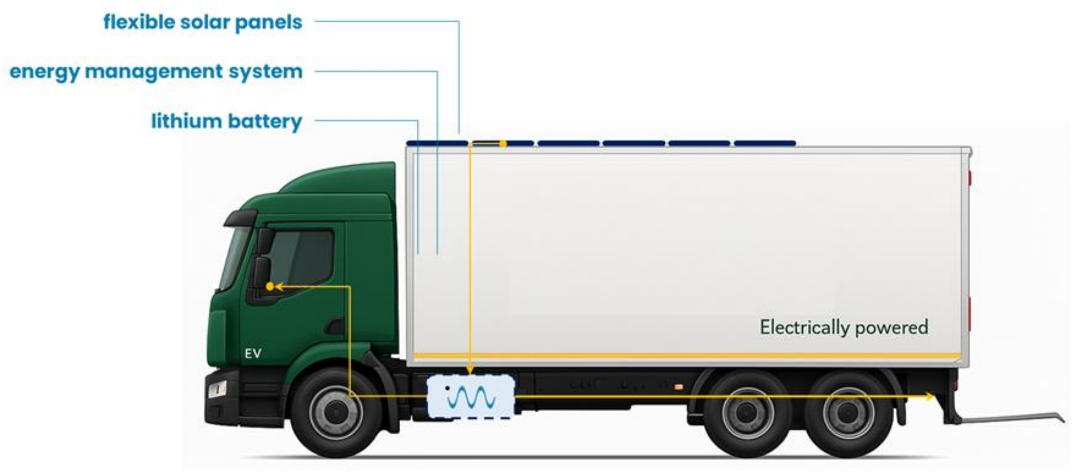


Figure 97: EV Rigid truck with SolarOnTop system from IM Efficiency

Figure 98 shows the percentage of monthly solar energy consumed from the SoT system between March and July 2025 from an electric rigid truck. Each green bar is the total average solar energy consumed by the EV during the operational days of a particular month, expressed as a percentage of total energy demanded by the electric truck. The graph below shows clear evidence of how much solar can actually aid an EV in a typical urban driving profile.

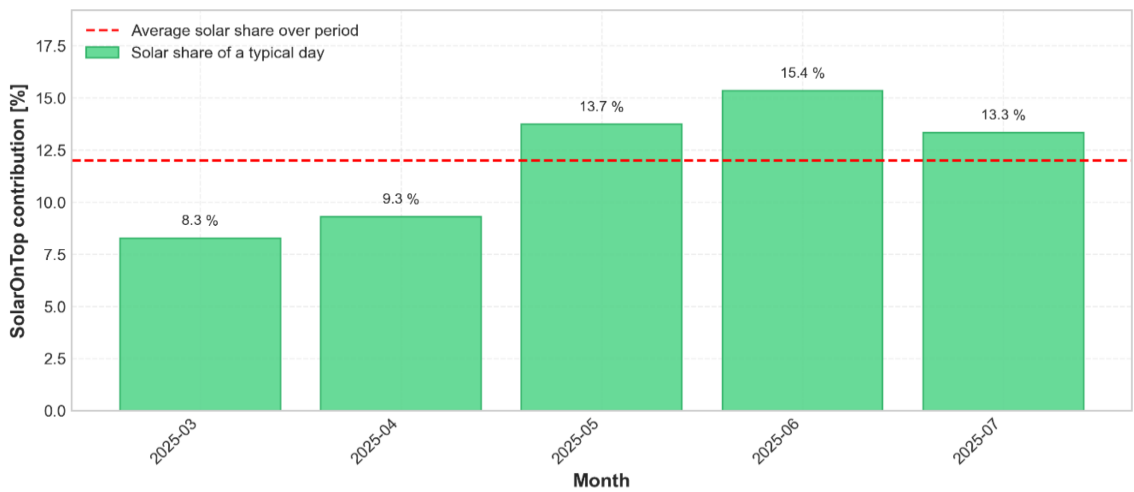


Figure 98: Percentage of Solar energy contributed to an Electric truck for daily operation

The red dashed line in Figure 98 represents the total average solar contribution over the whole period of March-July which is close to 12,4%. For a typical Dutch urban distribution route, an electric food truck may spend large part of the day in stop and go traffic, at loading docks or in urban delivery zones, where traction power is intermittent but local loads, on-board electronics and telematics run continuously. The SoT system harvests solar energy that would otherwise have been supplied by the main battery or by grid electricity during charging.

In other words, over several months of real operation, the top mounted PV consistently provides a double-digit fraction of an electric truck's daily energy needs, with the contribution peaking in late spring and summer when there is more solar availability

Conclusion and Outcomes

The measurements on Peugeot Boxer Luton, the three long haul distribution trucks and the result from one battery electric rigid truck demonstrate that VIPV can provide a robust and quantitatively meaningful source of on board energy for commercial freight operations in Europe. Three major factors which makes VIPV particularly compelling for commercial freight at this moment are,

I. Firstly the large, unobstructed surface area available on truck roofs and sides (90 m² on a typical tractor-trailer) far exceeds what is available on other typical architectural vehicles.
II. Secondly, commercial vehicles spend extended periods exposed to sunlight during loading, unloading, and inter-city transit, maximizing utilization of the installed PV capacity.
III. And thirdly, the high daily energy consumption of freight vehicles means that a 12–15% solar contribution translates into economically significant reductions in grid charging and/or fuel use. These characteristics position commercial VIPV as a higher-impact application with faster payback periods and greater emissions reductions per installed watt-peak.

In addition, the sensor placement and the direction of orientation of the vehicle has significant influence on the distribution of solar irradiance on vehicle surface, e.g. it is shown in the case study of the Peugeot Boxer Luton that the irradiance on the sides is about 50% of the top. Further theoretical analysis has been made in Appendix O where it has been discussed on how the 50% split on the sides is distributed between the top half and bottom half of the vertical side in a truck.

Based on the irradiance measurements from this project on heavy-duty architectures, VIPV systems on diesel trucks could avoid approximately 3,8 tonnes of CO_2 emissions per truck per year by reducing alternator load and fuel use which can be scaled to a fleet of about 4 million European trailers, this corresponds to approximately 15–17 million tonnes of CO_2 avoided annually. In the case of electric heavy duty trucks, the same measurements imply that, roof integrated VIPV alone can extend practical driving range by up to about 15% over the course of a year in the Netherlands, while in high irradiance regions such as Spain or southern Europe, range gains of 30–35% are possible scenarios for similar vehicle use profiles.

2.4.5. Sono Motors: Case study Bus in Nitra

Sensor Setup

Since Fraunhofer ISE sensors are designed for magnetic mounting on magnetic roofs, an alternative, non-permanent installation method was required for vehicles with non-ferromagnetic roofs, such as buses. To address this, Sono Motors designed and supplied a specialized mounting plate with an appropriate pulling force, ensuring secure attachment for all necessary vehicle installations. An example is shown in Figure 99.

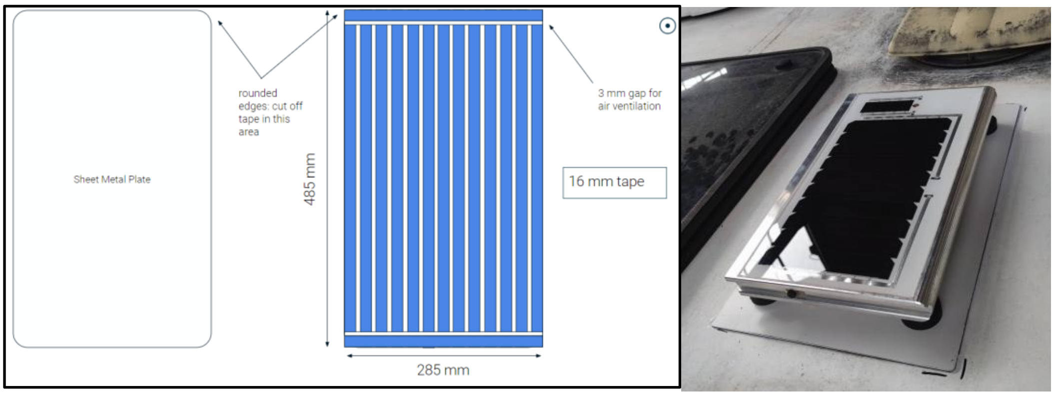


Figure 99: Non-ferromagnetic roof installation method for sensors

Solar Energy production from Buses

The irradiation measurement campaign results from two buses operating in the same city have been analysed to provide insights into solar energy potential. These buses operate in Nitra, a central European city, primarily serving urban and suburban routes. A heatmap of the routes is given in Figure 100.

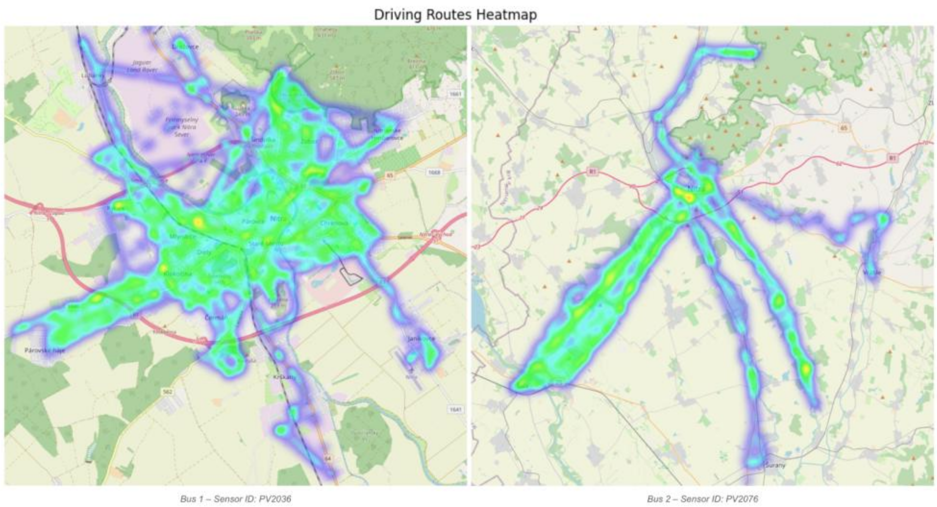


Figure 100: Driving Routes Heatmap

To ensure a valid comparison, only data from periods when both sensors were active and collecting measurements were included. Additionally, seasonal distribution and the yearly cyclic nature of solar were taken into account by incorporating data from summer, winter, spring, and autumn.

Table 37: Sensor Data Summary – PV2036 & PV2076

	Bus 1 – PV2036	**Bus 2 – PV2076**
Driving pattern	Urban	Urban & Sub-urban
Duration	01.07.2024–30.06.2025	
# of days	365	

Irradiation		
Total	1,110,447 Wh/m2	821,188 Wh/m2
Daily Maximum	8,012 Wh/m2	7,225 Wh/m2
Daily Average	3,042 Wh/m2	2,250 Wh/m2
Distance		
Total	46,327 km	53,855 km
Daily Maximum	244 km	450 km
Daily Average	127 km	149 km

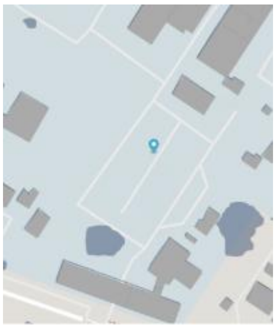
The real-life solar irradiance measurements from these urban buses provide valuable insights into the potential application of onboard solar energy in transit systems. Over the one-year monitoring period, the two buses exhibited distinct driving patterns, solar exposure levels, and potential solar yields, emphasizing the influence of route characteristics and operational conditions on solar energy availability.

Bus 1, primarily operating within the city centre, covered a total distance of 46,327 km, averaging 127 km per day with a peak distance of 244 km in a single day covered. Despite frequent stops, lower average speeds, and increased shading from buildings and infrastructure while driving, Bus 1 recorded a total irradiance of 1,110,447 Wh/m², corresponding to an average daily irradiance of 3,042 Wh/m².

In contrast, Bus 2, which primarily serves urban and suburban routes, travelled a greater total distance of 53,855 km, averaging 149 km per day. It followed longer, less interrupted driving patterns with higher average speeds, spending more time in open environments. However, despite its greater distance coverage, Bus 2 recorded a lower total irradiance of 821,188 Wh/m², corresponding to an average daily irradiance of 2,250 Wh/m².

While the difference in distance travelled by the buses is less than 20% as highlighted in the table above, Bus 2 was operational for only 60% of the duration compared to Bus 1. Bus 2 had higher driving speeds allowing it to cover more distance due to its mix of urban and peri-urban driving route. In addition to this, their respective parking locations can also have significant impact on the irradiance measurements. Bus 2 was regularly parked in a shaded depot surrounded by structures, whereas Bus 1 was stationed in an open environment with minimal shading. The shading profile for both buses at key times on July 1st—the first day of the analysed dataset is shown below:

Table 38: Shadowing – Vehicle parking locations

Date	1st of July		
Time	06:00	12:00	18:00
Bus 1 – PV2036			
Bus 2 – PV2076			

To further contextualize these findings, the irradiance measurements were translated into an estimated solar yield for a 1.4 kWp PV system covering ~7.5 m² of a vehicle roof area. Bus 1 demonstrated a potential solar yield of 1813 kWh over the calendar year, with peak earnings, outperforming Bus 2, which recorded a potential yield of 1338 kWh despite its greater exposure to open environments. Peak earnings potential for Bus 1 was measured at 13.13 kWh in a single day, while Bus 2 also showed double-digit peak earnings potential in a single day of 11.84 kWh. A plot of these results is presented below:

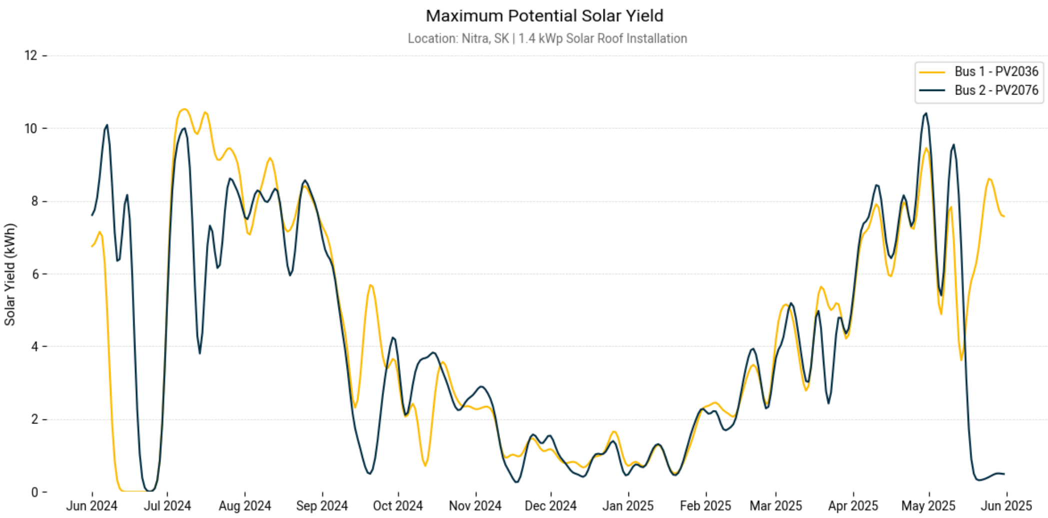


Figure 101: Comparison of Maximum Potential Solar Yield – PV2036 & PV2076

A further breakdown according to different seasons is shown below:

Table 39: Seasonal statistics – Potential Solar Yield per Bus

Season	Bus 1 – PV2036	Bus 2 – PV2076
Summer (May-Aug)		
Total	1059 kWh	610 kWh
Daily Average	8.61 kWh	4.96 kWh
Daily Maximum	13.13 kWh	11.84 kWh
Winter (Nov-Feb)		
Total	181 kWh	178 kWh
Daily Average	1.51 kWh	1.48 kWh
Daily Maximum	4.82 kWh	4.95 kWh
Shoulder (Mar-Apr, Sep-Oct)		
Total	573 kWh	550 kWh
Daily Average	4.67 kWh	4.51 kWh
Daily Maximum	10.38 kWh	10.99 kWh

Conclusion – Bus Case Study

The SolarMoves measurement campaign demonstrates a clear potential for vehicle-integrated photovoltaics (VIPV) in municipal transport applications. Real-life irradiance data from operational buses shows that solar energy can reliably provide 1300–1800 kWh per year per vehicle under Central European conditions.

While this represents a supplementary share of total bus energy needs, it directly contributes to reducing grid-derived electricity consumption, especially during summer months when energy demand is high. Differences between buses highlight the strong influence of route profiles, parking conditions, and shading.

Overall, the findings confirm that VIPV enhances the sustainability of bus fleets – ICE and electric alike, provides measurable operational energy, and supports long-term decarbonization strategies. The dataset produced through this campaign offers a strong foundation for further optimization and future VIPV system integration in public transport fleets.

2.4.6. Sono Motors: Case study Van

As part of the energy measurement campaign, Sono Motors conducted real-world testing to evaluate the energy generation, utilization, and integration of onboard PV in EVs.

Sono Motors, together in a partnership with Ford, has used in its testing an electric van – the Ford E-Transit equipped with a 1080 Wp solar system. The vehicle has undergone a series of nine test drives across different seasons. The test drives were conducted on a test track from Ford in Northern Europe.

Methodology and Setup Vehicle and PV System

- **Test Vehicle:**
  - Model: Ford E-Transit; 4.25T N2 Class vehicle;
  - Battery Capacity: 68 kWh battery; ≈60-62 kWh (estimated usable capacity)
  - Model Year: 2022.5;
  - Archetype: LV21, Local Distribution
- **Onboard PV System:**
  - PV Capacity: 1080 kWp solar panels mounted on the vehicle roof and left side.
  - Integration:
    - High-voltage (HV) solar charging for the traction battery
    - Low-voltage (LV) charging for the 12V auxiliary system

Test Drive Protocol

Each test drive followed a standardized protocol simulating a typical urban parcel delivery route. The key parameters of the test protocol include:

Each test cycle lasted a full day during sunshine hours, capturing variations in irradiance and energy demand. The nine test drives covered seasonal variations to evaluate solar performance under different weather and daylight conditions while maintaining consistent driving behaviour and operational pattern across tests on a repeated route on the controlled Ford test track.

Results from the Test Drives

For each test drive, several data parameters were collected. These are given in Appendix L

Below we have compiled the results from the test drives conducted between January–June 2025. The route for the test drive on the test track is shown below:

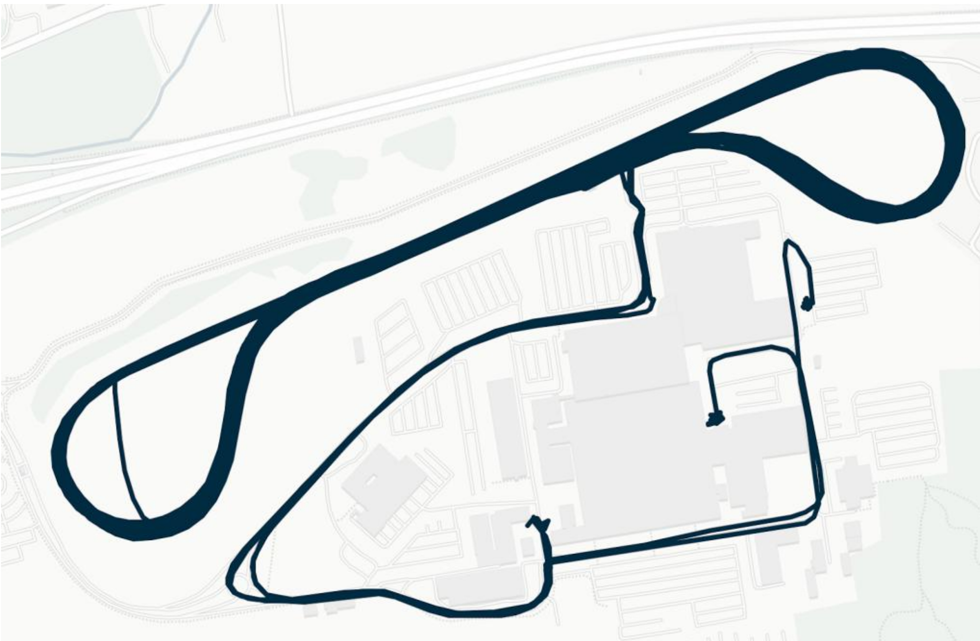


Figure 102: Test Track and Driving Route

Table 40: E-Van Test Drive Plan

Pretest Preparations	Full overnight charge to 100%, SOC. Load vehicle with 125kg Payload. Pre-condition HV battery for warm-up for estimated departure time from overnight charging point (Not required if indoors or above 10°C ambient)			
Time	**State**	**Activity**	**V_{max} [kph]**	**Guidelines**
08:00	Parked on-plug	Pre-test preparations	0	Leave vehicle on charge by HS hut. Key-off (simulates loading parcel payload and route planning). Set vehicle speed and limiter to kph units. Vehicle to be put into EcoMode SDM. Aux load such as HVAC/Heated seats, radio and heated windscreen are permitted and to be used as required. 6.5kW charge power
08:30	Driving	Start route depot to highway (suburban segment)	60	Set vehicle speed limiter to 60kph and maintain across entire lap of track.
08:45	Driving	Depot to city centre (highway segment)	90	Set vehicle speed limiter to 90kph and adjust accordingly around bends.
09:15	Driving	Delivery loop (urban segment)	30	Set vehicle speed limiter to 30kph and maintain across entire lap of track f HS track with 2 min stop at hut. (1hr duration)Key-off for duration of stop.
10:15	Driving	Return to depot (highway segment)	90	Set vehicle speed limiter to 90kph and adjust accordingly around bends.
10:45	Driving	Return to depot (suburban segment)	60	Set vehicle speed limiter to 60kph and maintain across entire lap of track.
11:00	Parked on-plug	Simulated reloading, charging & lunch break	0	Leave vehicle on charge by HS hut. Keyed-off (simulates loading parcel load and route planning) 6.5 kW charge power for ~2hrs
13:00	Parked on-plug	Simulated top up, charge on lunch break	0	Move vehicle to DCFC station. Keyed-off (simulates loading parcel load and route planning) 115 kW charge power for ~45mins
14:00	Driving	Start route to depot (suburban segment)	60	Set vehicle speed limiter to 60kph and maintain across entire lap of track.
14:15	Driving	Depot to city centre (highway segment)	90	Set vehicle speed limiter to 90kph and adjust accordingly around bends.
14:45	Driving	Delivery loop (urban segment)	30	Set vehicle speed limiter to 30kph and maintain across entire lap of track f HS track with 2 min stop at hut. (1hr duration)Key-off for duration of stop.
15:45	Driving	Return to depot (highway segment)	90	Set vehicle speed limiter to 90kph and adjust accordingly around bends.
16:15	Driving	Return to depot (suburban segment)	60	Set vehicle speed limiter to 60kph and maintain across entire lap of track.
16:30	Idle	End test	0	Exit HS track, park vehicle and key-off

Across all nine test drives, the Ford E-Transit completed an average distance of 287 km per cycle. The onboard solar system generated an average of 1.73 kWh of energy per day throughout the entire test campaign, with solar yields increasing to 2.68 kWh during the summer test drives conducted in May and June. This progression reflects the expected seasonal improvement in irradiation levels. Figure 103 illustrates the solar energy yield for each test day, highlighting the clear correlation between seasonal solar availability and onboard solar system output.

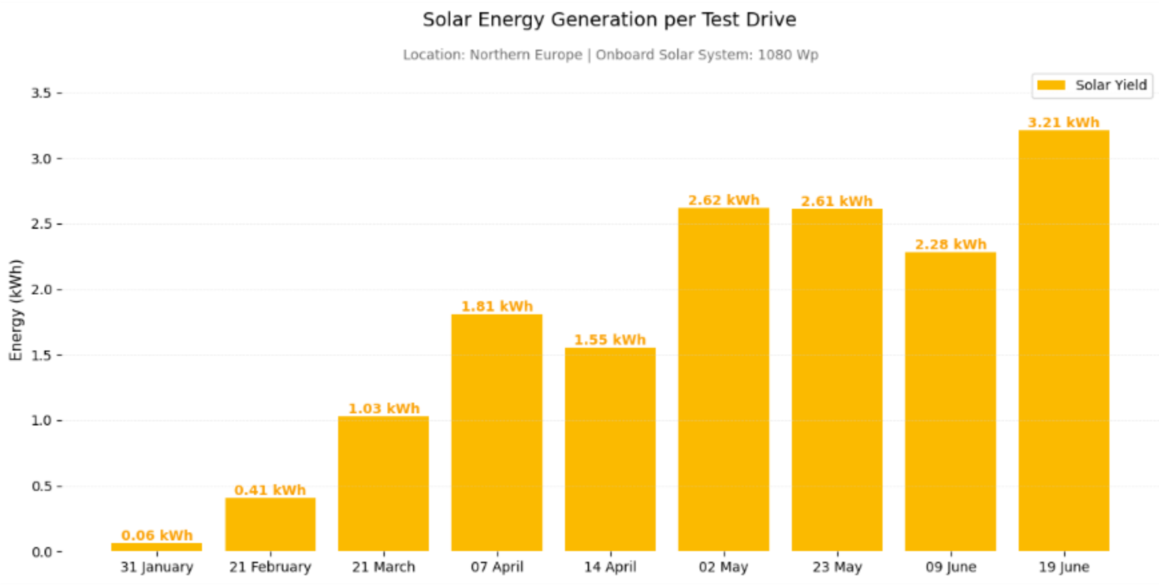


Figure 103: Solar Yield during test drives

The State of Charge (SoC) profiles for the traction battery recorded during the drives revealed two major discharge phases corresponding to morning and afternoon vehicle operation, separated by a mid-day recharging break. Early in the campaign, the vehicle utilized DC fast charging during this break, resulting in rapid replenishment but reduced opportunity for concurrent solar charging during peak sunshine hours around noon. As the testing progressed, the charging strategy was adjusted to use more AC charging during the break. This change, combined with improving seasonal irradiation, enabled the solar system to contribute more effectively during idle periods. The figure below shows the battery state of charge over the course of the test drives from an earlier test drive in February versus after optimisation at a later test drive in May.

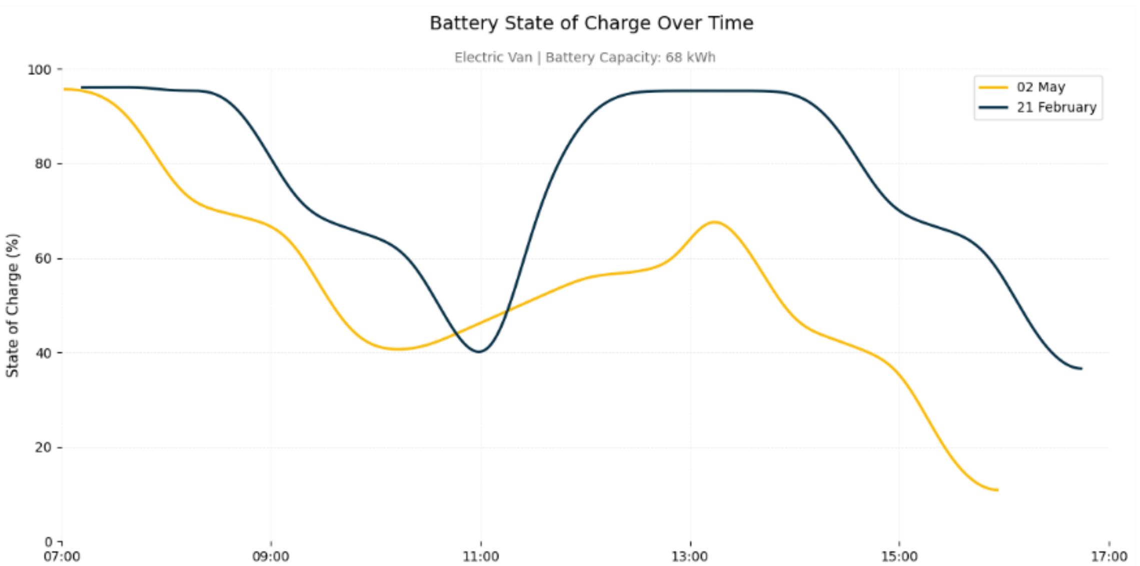


Figure 104: Vehicle SoC over entire test drive – Before and after the optimisation of charging cycles during breaks

The contribution of solar energy to the vehicle's charging needs grew significantly over the course of the campaign. In the early winter test drives, the solar system contributed as little as 0.12% to the total recharging demand. By contrast, during late spring and early summer, solar coverage increased to as much as 12.54%, with an overall campaign average of 4.40% and a summer-specific average of 9.08%. Figure 105 visualizes the balance between plug-in charging from the grid and solar charging from the PV modules across the nine cycles.

In addition to recharging contributions, the analysis examined how much of the total energy consumption during each test drive was covered by onboard solar. During peak winter conditions, solar accounted for just 0.06% of the energy needs of the vehicle, whereas by June this increased to 4.10%. Over the entire test period, the average solar yield of 1.73 kWh corresponded to 2.13% of total consumption, while the summer average of 2.68 kWh translated to 3.42%.

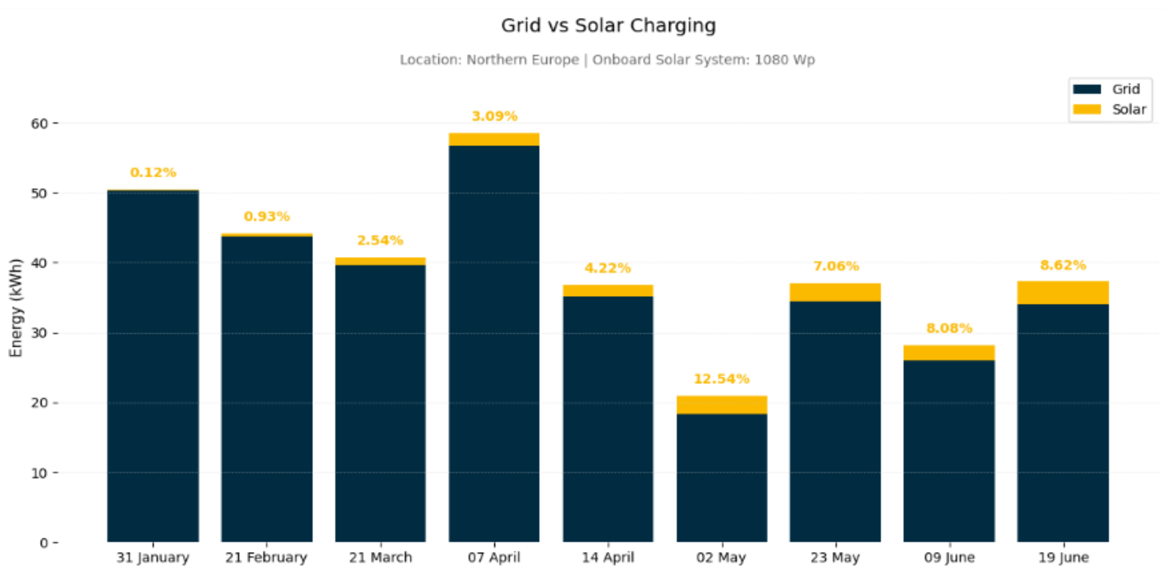


Figure 105: Recharging during test drives – Grid vs Solar

The energy provided by the solar system to both the high-voltage traction battery and the low-voltage auxiliary battery delivered a measurable impact on operational range and charging behaviour. On average, the PV installation enabled an additional 6.32 km of driving per test cycle, rising to 9.90 km during the summer months. This additional range reduced the time required at the AC charger by up to approximately seven minutes—around 5% of the typical 40 kWh recharging session per test drive. A consolidated overview of all key performance indicators from the campaign is presented in Table 41.

Further Outcomes

The results and learnings from the test campaign have directly informed Sono Motors' strategy for improved solar integration in future van platforms. Key advancements include increasing the total installed solar capacity through higher watt-peak (Wp) PV modules, optimizing the PV cabling and module installation to reduce overall impact on total vehicle energy consumption through better aerodynamics, and expanding the installation area to both sides of the vehicle. In addition, optimized charging profiles and enhanced power electronics are being introduced to improve overall system efficiency. The insights gained from real-world performance have also been incorporated into significant updates to Sono Motors' proprietary simulation model, leading to more accurate predictions of energy yield and operational benefits.

Table 41: Summary Statistics – All Test Drives

Test Drive	Distance	Vehicle Consumption	Solar Yield	Yield vs. Consumption	Yield vs. Recharging	Additional Range
31 Jan	280.73 km	93.60 kWh	0.06 kWh	0.06%	0.12%	0.18 km
21 Feb	286.15 km	83.13 kWh	0.41 kWh	0.49%	0.93%	1.41 km
21 Mar	293.88 km	80.93 kWh	1.03 kWh	1.28%	2.54%	3.75 km
7 Apr	276.62 km	75.85 kWh	1.81 kWh	2.38%	3.09%	6.59 km
14 Apr	290.38 km	83.71 kWh	1.55 kWh	1.85%	4.22%	5.38 km
2 May	293.04 km	79.32 kWh	2.62 kWh	3.30%	12.54%	9.68 km
23 May	285.14 km	76.41 kWh	2.61 kWh	3.42%	7.06%	9.75 km
9 Jun	290.11 km	80.07 kWh	2.28 kWh	2.85%	8.08%	8.27 km
19 Jun	290.77 km	78.48 kWh	3.22 kWh	4.10%	8.62%	11.91 km
Overall Average	**287.42 km**	**81.28 kWh**	**1.73 kWh**	**2.13%**	**4.40%**	**6.32 km**
Summer Average	**289.77 km**	**78.57 kWh**	**2.68 kWh**	**3.42%**	**9.08%**	**9.90 km**

Applying this updated concept to simulations conducted at the same Northern European test location demonstrated notable performance improvements. The enhanced system is capable of contributing up to 4.74% of the vehicle's total energy consumption on average during the peak month of June as shown in Figure 106. Under these conditions, the average additional driving range provided by the onboard solar system increases to 11.84 km, showcasing the potential of the refined concept to deliver substantial value to end users, particularly in delivery and fleet use cases.

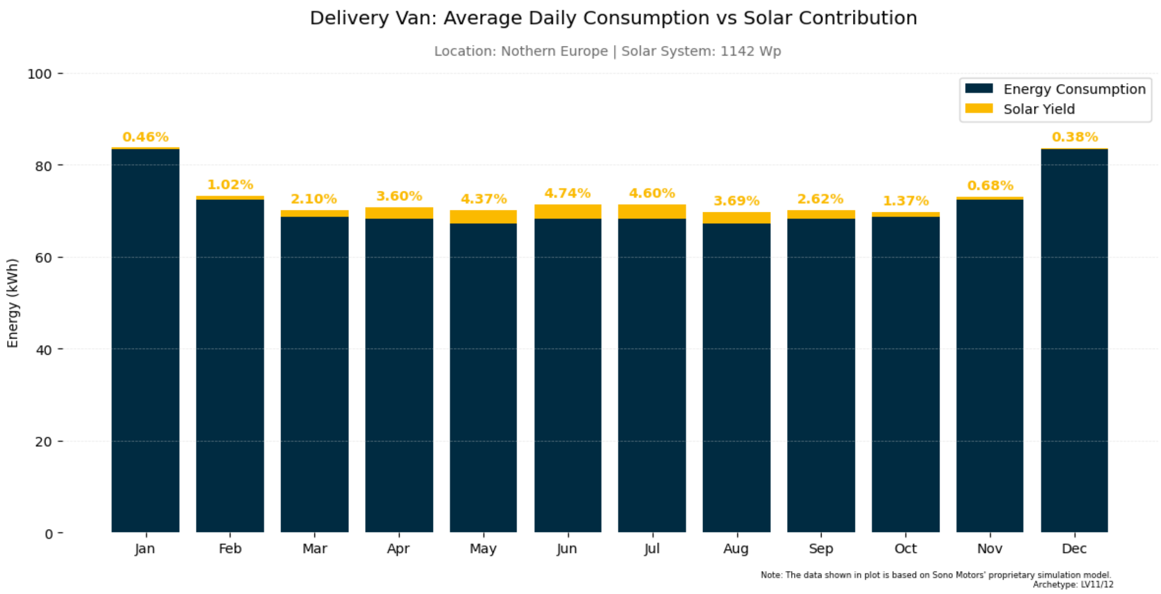


Figure 106: Simulation: Delivery Van Consumption vs. Solar Yield on a new & improved concept

Conclusion – Electric Van

The test campaign conducted demonstrates the clear potential of onboard PV systems to enhance the operational efficiency of electric delivery vehicles. Despite the challenges posed by winter conditions in Northern Europe, the PV-equipped Ford E-Transit consistently generated measurable solar energy, achieving meaningful contributions during spring and summer months.

Across nine standardized test drives, the system provided up to 12.54% of the vehicle's daily charging needs in summer and delivered tangible operational benefits, including extended range, reduced dependency on charging infrastructure, and shorter charging stops. These results confirm that PV integration can play a valuable role in supporting last-mile delivery fleets, particularly in regions with favourable irradiation.

The insights gained from real-world operation have already helped shape Sono Motors' next-generation solar integration concept and simulation models. With higher PV capacity, improved placement, and optimized charging behaviour, future implementations are expected to yield even greater energy contributions and stronger ROI for fleet operators.

Overall, the findings here validate the technical feasibility and practical value of onboard solar integration for electric vehicles and provide a strong foundation for further development and scaling within commercial fleet applications.

2.4.7. Conclusion

The energy measurements have been executed with three vehicles, one from each company involved in the project. The vehicles tested range from a highly efficient VIPV passenger car to a fully electric van and data from fully electric trucks.

The energy measurements of the VIPV passenger vehicle show an exemplary reduction of the energy consumption from 111.6 Wh/km to 81.3 Wh/km from solar energy feed in to the battery.

The energy consumption model for passenger cars and trucks as developed in Chapter 1 has been evaluated and gives a good result for truck, van and passenger car categories. As such it is a realistic model to determine the impact of VIPV.

While Section 2.4 presented in-depth case studies illustrating the real-world performance of VIPV in specific operational contexts, the following section places these findings in a broader perspective. Section 2.5 benchmarks the PV integration results against other studies, vehicle concepts, and reference approaches, allowing the project outcomes to be positioned relative to existing knowledge and alternative solutions.

2.5 Benchmarking of PV Integration results

This paragraph benchmarks the energy yield of vehicle-integrated photovoltaics (VIPV) against equivalent PV capacity installed in static systems. Using the installed watt-peak (Wp) capacity projected for the 2030 fleet scenario, the analysis compares VIPV performance with optimally oriented land-based PV installations in Amsterdam and Madrid, as well as with common configurations such as balcony PV systems. This assessment provides insights into relative efficiency, infrastructure implications, and the trade-offs between mobile and stationary PV deployment.

2.5.1. Technical comparison

Focusing on the technical aspects we compare the energy yield of the mobile PV, as reported in the first interim report, with what the same amount of PV installed in static systems may yield. By the same amount we mean the total Wp installed.

In the first instance we compare the yield from paragraph 1.4.1 with PV installed in the optimum configuration. South facing and at the optimum tilt for the location – again looking at Amsterdam and Madrid. This provides an upper limit to static PV yield. We then consider different system configurations, based on the commonly installed systems in the Netherlands and Spain. Using published reports, we estimate the proportion of the different system types that make up the national installed PV and apply this distribution to the amount of PV from the first report that will be installed in static systems. To calculate the yield from these systems we use the online tool, Global Solar Atlas, using its determined specific yield of the different system types per location and then multiply these specific yield values by the installed PV to obtain the final yield.

2.5.2. Determine installed PV on fleet

In the first part of the project we looked at 4 scenarios, present day (2023), 2025, 2030 and Ultimate. In this stage we consider the 2030 results only.

The following approach has been used to determine the potential for installed PV on the European electric vehicle fleet:

- Collect the number of each vehicle type in the EU fleet predictions
- Collect the PV area and efficiency for each vehicle and scenario
- Calculate the installed Wp on each vehicle for each scenario
- Combine the number of vehicles and the Wp installed to estimate the total installed PV [MWp] for each scenario
- Determine the specific yield for the different static PV installations
- Compare with the kWh generated from VIPV in 2030

Total installed Wp on the EU fleet

We used the number of vehicles per archetype in the EU fleet as determined in the first phase, see Table 42.

Table 42: the quantity of vehicles for each vehicle group for the EU

	number in fleet [million]		
Vehicle type	**2023**	**2025**	**2030**
Small passenger car	1.06	2.47	7.87
Medium passenger car	1.16	2.70	8.62
SUV	0.88	2.05	6.54
Small van	0.05	0.10	0.30
Large van	0.07	0.13	0.40
low-floor bus	0.01	0.08	0.29
high-floor coach	0.00	0.00	0.00
Rigid truck	0.00	0.00	0.05
Tractor-trailer	0.00	0.00	0.03

The area available for PV as used in the first phase, see Table 43, was then multiplied by the number of vehicles per archetype. Taking into account the estimated efficiency of the VIPV in 2030 of 23%, gives the total amount of Wp that is installed on the fleet and is given in Table 44, for top installation, sides installation and top and side installation.

Table 43: PV area per vehicle

	Available PV area [m2]	
Vehicle type	Horizontal Sun facing surfaces	Vertical sides (per side)
Small passenger car	2	0.7
Medium passenger car	2.64	0.95
SUV	4.2	1.2
Small van	4.26	1.23
Large van	6	1.75
low-floor bus	8	3.54
high-floor coach	8	3.54
Rigid truck	14	16
Tractor-trailer	25	28

Table 44: Total installed PV for the fleet – per scenario

	2030		
Vehicle type	2030 Total Top [MWp]	2030 Total Sides	2030 Total [MWp]
Small passenger car	3620	2534	6155
Medium passenger car	5231	3765	8996
SUV	6321	3612	9933
Small van	298	172	470
Large van	553	323	876
low-floor bus	535	474	1009
high-floor coach	0	0	0
Rigid truck	147	335	482
Tractor-trailer	159	357	516
Totals MWp	16864	11571	28436
Totals GWp	16.9	11.6	28.4

2.5.3. Determine the generated PV energy if the installed PV was in static systems

Using the above installed capacity in combination with the specific yield for a system (kWh/kWp installed capacity) gives the kWh that could be generated if that capacity was installed in a static system.

The specific yield for an optimal oriented system in Amsterdam is 1047 kWh/kWp and in Madrid 1654 kWh/kWp[45], resulting in overall PV yield for the 2030 as depicted in Figure 107 for Amsterdam and Madrid and compared with the VIPV energy generated on the vehicles and actually used, for

[45] Global Solar Atlas

PV on top and PV on the sides as was calculated in T2.1.1. In the numbers of the static system transport losses from the PV plant to the vehicle are taken into account. These are country dependent but are 7% on average for the EU.[46] Clearly installing the PV panels in the optimal configuration in Amsterdam and Madrid generates more energy than the same panels on the vehicles.

But, as there is a tendency in the Netherlands, and maybe other countries as well, to block land based static installations, comparing with land-based systems is not in all cases realistic. Besides that, overall costs will also play an important role. To bring the generated energy to the vehicle, additional investments are needed for: EV charging points for charging of all these vehicles and more grid reinforcement.

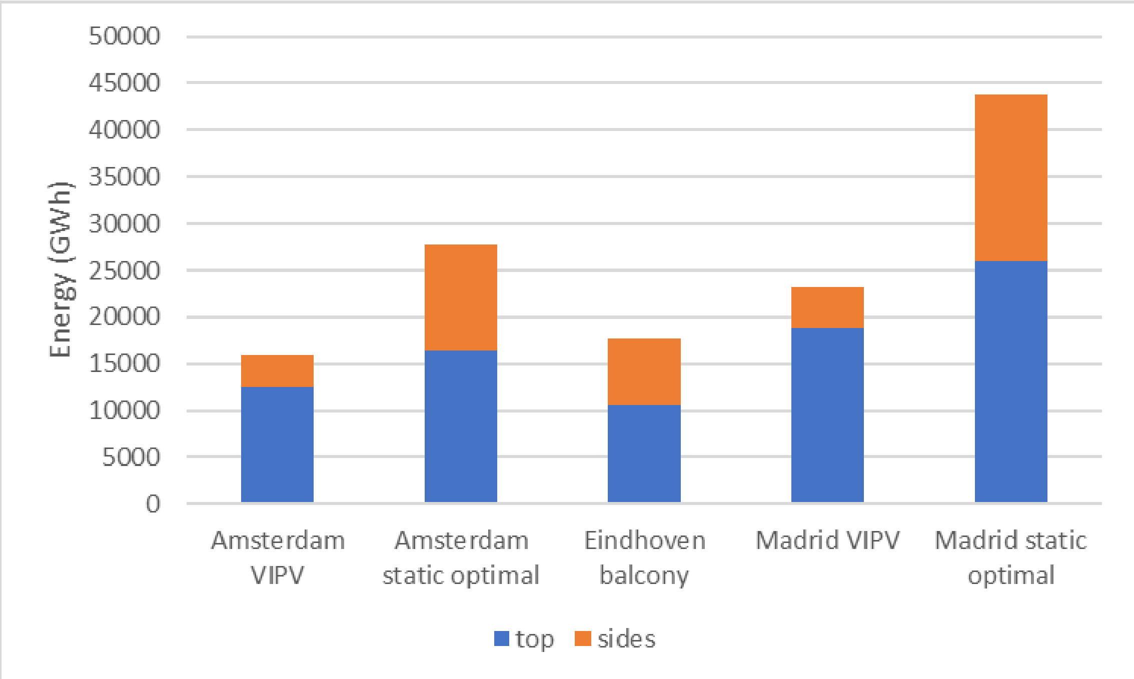


Figure 107: Energy generated by static land-based PV plants and for balconies in Eindhoven, the latter serves as a typical situation for balconies in the Netherlands, and compared to the used Solar Energy that is generated by the VIPV fleet

For this reason, we also compared the VIPV results with static PV in BIPV in balconies of apartment buildings. So-called balcony PV is very similar to many aspects of VIPV. Specifically:

- System size: The order of magnitude of the size of the system is similar in addition to potential area;
- Installation: Balcony solar is rarely installed at optimal tilt angle and often will have more shading impact than open-field installations;
- Energy use: Generated electricity is used directly at the location where it is generated avoiding the grid investments of the static land-based PV systems; and
- Other: Apartment dwellers are considered a target group for VIPV adoption as they often cannot secure private charging options. Therefore, the socio-economic and user profile is likely similar.

[46] Electric power transmission and distribution losses (% of output) | Data

In the BOUWDIT project[47], the energy yield of a bifacial balcony PV systems was determined for element facing West. The results show an energy yield of 624 kWh/kWp. A similar value can be assumed for an East facing balcony. South facing balconies would generate more, so by using the 624 kWh/kWp would give an underestimation of the potential. Figure 107 also shows the energy generated by these balconies if all the PV modules of the VIPV were installed on balconies. As can be seen, installing the PV on the balconies gives a similar amount of kWh's as the VIPV.

2.5.4. Conclusions

A benchmark was performed of the generated energy by the VIPV fleet in 2030 as compared to the energy that could be generated by the same amount of Wp installed in a static land-based system or a static balcony system. The results show that for both Amsterdam and Madrid the land based system under optimal tilt gives a substantial higher yield. The energy generated in such a system however needs to be transported to charging stations, which will result in additional costs for both the transport grid as well as the charging stations. The grid reinforcement could to some extent be avoided by placing the systems near or on the charging stations. Placing the PV on balconies of apartment buildings results in a rather similar yield. The calculations were done for a West facing system but would be similar for an East facing system and even higher for a South facing system. This shows that energy-wise the balconies would be a good alternative for VIPV. It would need less grid reinforcement as the energy is in many cases generated where it is needed. However, as most of the apartments owners cannot connect their EV to their balcony solar system, the energy needs to be fed back into the local grid, which means extra losses and possible local grid reinforcement. On the other hand, balcony installations are also considered for generation of the household energy needs itself and could be limited to generate the excess energy needed for the charging of the BEV. A dedicated study would be needed to determine the potential for the BEV charging. Additional to the reduction in grid reinforcement, VIPV offers drivers convenience due to the increased driving range, or less charging moments. Please note that the benchmark with energy generated by PV on balconies will mainly be relevant for passenger cars. For e.g. truck and buses, PV charging stations will be needed, which again would need substantial grid reinforcement.

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[47] Topsector Energy subsidy provided by the Dutch ministry of Economic Affairs (TGOM120009, BOUWDIT)

3. Value Case Methodology & Policy Recommendations

3.1 Objective

This chapter on task 3 presents a combination and interpretation of the results of Task 1 and Task 2 in order to draw meaningful conclusions about the potential of on-board PV in the future EU transportation sector. Likely future scenarios up to 2030 are identified for the balance of on-board PV and stationary charging, based on an economic analysis, externalities, and other costs and benefits for vehicle owners and other stakeholders. Task 3 presents an analysis of the financial and non-financial costs and benefits for all stakeholders. To ensure a consistent multi-stakeholder assessment, it applies the Value Case Methodology (VCM), which provides a structured way to compare effects across actors and scenarios. The insights from this cost–benefit analysis form the foundation for the policy recommendations presented later in this report (paragraph 3.5).

3.2 Value case methodology

The Value Case Methodology (VCM) described by Dittrich (2015)[48] is a well-established method for multi-actor, multi-criteria decision analysis, which can map out costs and benefits and identify mechanisms to share them (see Figure 108). It includes a number of steps, which take data collected from analyses as well as from interviews with key stakeholders, to construct an objective valuation. This is then used as the basis for policy recommendations (paragraph 3.5).

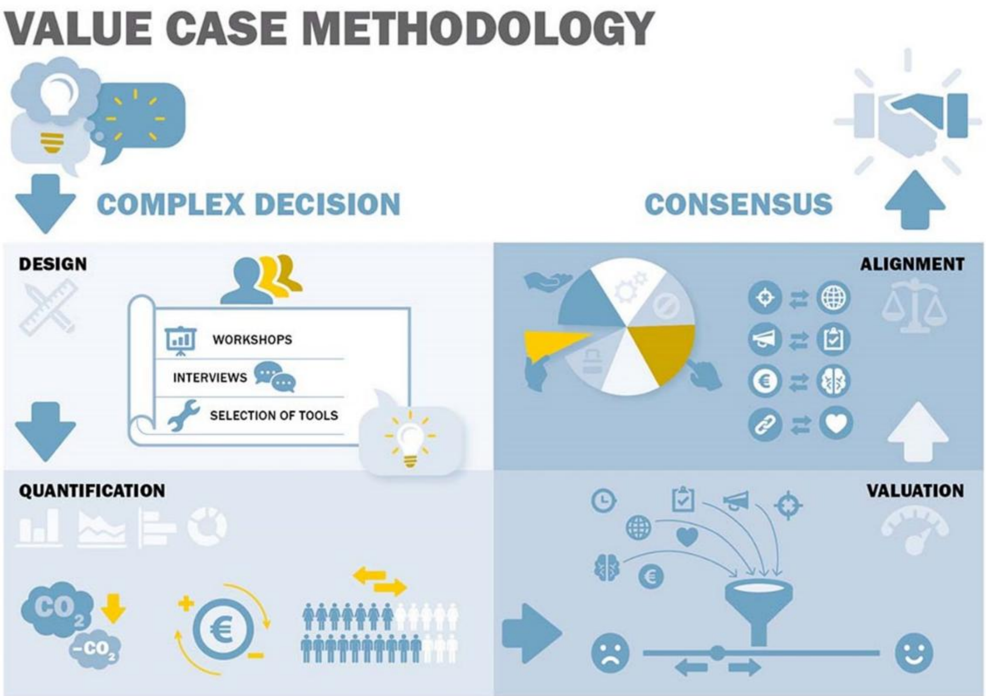


Figure 108: Value Case Methodology

[48] Dittrich, K. (2015). The value case methodology: A methodology aligning financial and non-financial values in large multi-stakeholder innovation projects. https://publications.tno.nl/publication/34614766/c3hDrW/dittrich-2015-value.pdf

As a first step in the Value Case Methodology, interviews were conducted with identified stakeholders, both inside and outside the Solar Moves consortium. The purpose of the interviews was primarily to identify the key stakeholders in the VIPV system and the effects VIPV has on the transport ecosystem. Additionally, relevant costs and benefits (both financial and non-financial) were identified that were considered in the analysis.

The interviewees are listed in the following table.

Table 45: List of interviewees

Stakeholder	**Role of organisation**	Role of interviewee
DG MOVE	Policy maker	Policy expert
Rijwiel & Automobiel Industrie (RAI)	Dutch association for the Automotive industry[49]	Industry representative
Lightyear	Industry, VIPV for consumer vehicles	Company representative
Sono Motors	Industry, VIPV for buses and vans	Technical specialist
IM Efficiency	Industry, VIPV for trucks	Company representative
Fraunhofer ISE	Research institute	Research expert
TNO	Research institute	Research expert

The effects of VIPV on grid operators, charging infrastructure operators and energy companies have already been analysed in Chapter 1, so no additional interviews were performed with these stakeholders.

The summaries of the interviews can be found in Appendix N of this report.

The insights from the interviews have been used as input for the following steps in the VCM:

1. Stakeholder mapping and scenario development (Paragraph 3.3.1 and 3.3.2)
2. Identification and valuation of costs and benefits (Paragraph 3.4)
3. Policy recommendations (Chapter 3.5)

The interviews confirmed the most relevant stakeholder groups and helped refine which benefits and trade-offs matter in practice, which are then formalised in the stakeholder mapping and scenario set-up below.

[49] As no explicit consent has been received from the interviewee of the RAI on the publication date, the corresponding interview summary is not included in Appendix N2.

3.3 Stakeholders and scenarios

3.3.1. Stakeholders

The costs and benefits related to the adoption of VIPV are distributed unequally across a wide range of stakeholders. The stakeholders considered in the current analysis are:

- Policymaker (government)
- OEM / Car Manufacturer
- Solar Solution (VIPV) Manufacturer
- Grid Operator
- Charging Point Operator
- Energy Company
- Vehicle owner (consumer)
- Vehicle owner (business)

Each stakeholder is impacted differently as a result of the adoption of VIPV, and the magnitude of these impacts also varies depending on their role within the system. In addition to these stakeholders, other parties play a role in the VIPV adoption process, such as car sales organisations and maintenance companies. Stakeholders that have not been included in the value networks were assessed to have little or no influence on VIPV adoption, and vice versa.

To obtain an understanding of how costs and benefits are distributed across stakeholders and how these stakeholders can influence others, two value networks are presented: one for commercial vehicle owners and one for private vehicle owners. This is done because relationships between stakeholder differ for these types of consumers. The networks visualise the main interactions between stakeholders through financial or information exchange, activities or products / services. Mapping these value flows is the first step in assessing how costs and benefits arise across market relationships.

Value network for commercial vehicle owners

The value network for VIPV from the perspective of commercial fleet operators reveals a complex interplay of incentives, investments, and impacts across multiple stakeholders. Currently, the purchase of VIPV systems for heavy-duty vehicles is typically done as add-on or retrofit to existing trailers and is therefore carried out by commercial fleet operators. EU emission reduction targets for heavy-duty vehicles, as set out in Regulation (EU) 2019/1242, are imposed on manufactures and OEMs and are measured through frameworks such as VECTO. Because VIPV products are sold directly by the solar solution provider to fleet operators, there is no regulatory mechanism pushing the end user to adopt these systems. Any emissions reductions in case of VIPV adoption do not count toward OEM compliance or appear in VECTO reporting at this time.

As a result, adoption of VIPV in heavy duty vehicles by fleet operators is driven solely by commercial considerations, such as reducing operational costs, contributing to internal sustainability goals, enhancing brand image or improving reliability of auxiliary systems. This direct purchase relationship between solar solution providers and commercial fleet operators limits policymakers' leverage to incentivise emission reductions through VIPV. The regulatory framework primarily targets OEMs, while investment decisions lie with fleet operators.

Value network for commercial vehicle owners (heavy-duty vehicles)

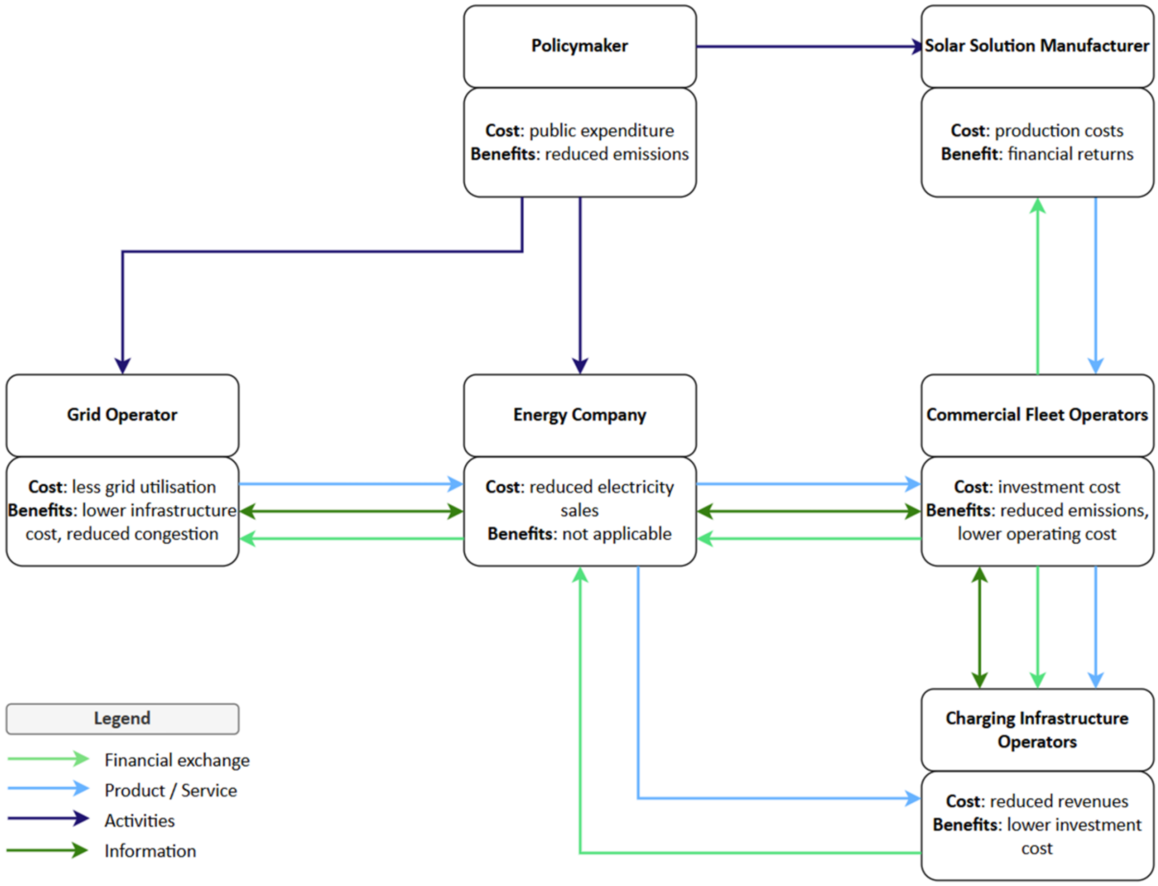


Figure 109: Value network for commercial vehicle owners (heavy-duty vehicles)

Another complication arises from the fact that trailers and trucks are not always owned by the same entities. In these cases, the costs and benefits are divided unequally across these two parties. Namely, the trailer owner bears the upfront investment costs for VIPV, while most benefits are experienced by the truck operator from the reduced fuel consumption and operational costs savings. This misalignment of costs and benefits can further slow adoption, as the incentives for each party are not fully aligned.

Another observation is that organisations involved in electricity provision through the grid – grid operator, CPOs and energy companies – could face a reduction in revenues if VIPV adoption reduces the demand for EV charging from the grid. While this may lower income from electricity sales, it also brings potential benefits: reduced peak congestions and lower investments needed in grid reinforcements. This shift in the network means that financial advantages gained by solar solution manufacturers (through the sales of VIPV products) and fleet operators partly come at the expense of traditional revenue streams for grid-related organisations. However, these negative effects may be offset by previously mentioned operational benefits. Moreover, the relative reduction in electricity demand from the grid as a result of VIPV may not be as significant in the broader context, as the electrification of transport overall will substantially increase electricity consumption.

Value network for private vehicle owners (light-duty vehicles)

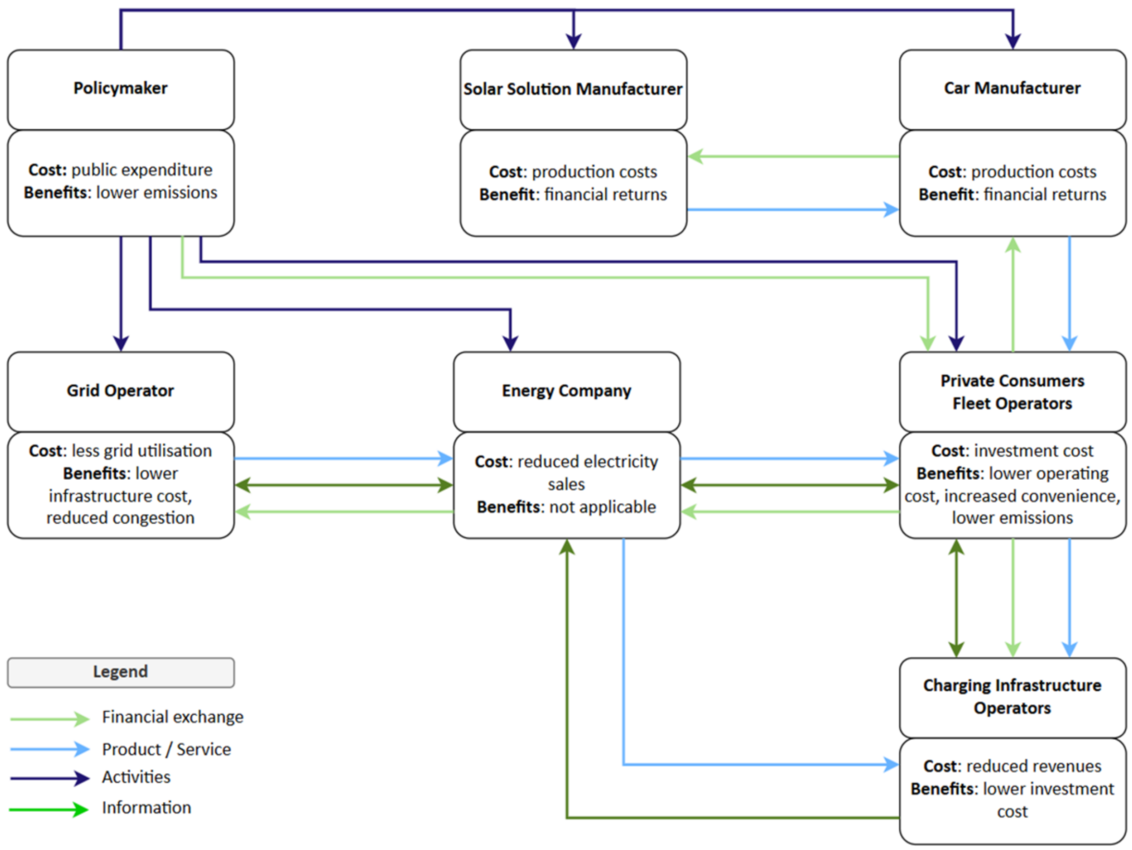


Figure 110: Value network for private vehicle owners (light-duty vehicles)

Value network for private vehicle owners

Similar to the previously described value network for commercial fleet operators, the value network for VIPV from the perspective of private consumers (light duty vehicles) reveals a complex interplay of incentives, investments, and impacts across multiple stakeholders. However, there are differences in the relationships between stakeholders in both value networks, also resulting in a different distribution of costs and benefits.

A key difference lies in the end-consumer of the solar solution (VIPV) product. For heavy-duty vehicles, the end-consumer is typically the commercial fleet operator. In contrast, for light-duty vehicles, the end-consumer of the VIPV product is the OEM or car manufacturer. Here counts as well that EU emission reduction targets for light-duty vehicles, set out in Regulation (EU) 2019/631, are imposed on these manufacturers. Since OEMs and car manufacturers are both the regulatory target and the direct purchaser of VIPV products, policymakers have more direct influence on the reduction of emissions through VIPV. A potential complexity, however, is that OEM and car manufacturers act as a gatekeeper in the system: private vehicle owners can only adopt VIPV if the manufacturer chooses to integrate it into vehicles. Although consumer demand (from private vehicle owners) can exert some indirect influence on these decisions, this influence is limited compared to the role of manufacturers.

Although the OEMs and car manufacturers bear some of the benefits of VIPV, such as reduced vehicle emissions, the upfront investment is largely passed on to the private vehicle owners through higher vehicle prices. For widespread adoption, the perceived benefits of VIPV for the end-consumer must outweigh these additional costs. Next to that, the same logic as in the previous value network applies here on the effects of VIPV adoption on grid-related organisations.

3.3.2. Scenarios

To calculate the financial benefit for the uptake of VIPV in Europe, three scenarios have been developed. The scenarios open a broad bandwidth of illustrative uptakes to paint a broad picture. These scenarios are used as part of the cost-benefit analysis.

The VIPV scenarios build on the EV uptake scenario developed in Task 1. It gives a projection of EV for 2025 and 2030 for the relevant vehicle types for EU27.[50] Three scenarios for possible uptakes of VIPV sales were developed based on this scenario: *Low Uptake* with limited integration, *High Uptake* with higher expansion and *High Uptake PLUS* with an increased sale in EVs because of a higher integration of VIPV. The scenarios are further explained in the following:

Low Uptake

VIPV is adopted only in niche segments, primarily in commercial vehicles such as long-haul trucks, delivery vans, and buses. In the passenger car segment, VIPV remains a novelty feature, marketed more for prestige or sustainability signalling than for utility. Consumers are generally not inclined to pay the extra upfront costs for VIPV, and car manufacturers offer it only as a high-end option.

The adoption is limited to 3% in cars and 10% in heavy duty vehicles from 2030.

High Uptake

VIPV becomes a standard option in light commercial and passenger vehicles, supported by falling production costs, better energy yields, and smart energy management systems. Regulatory incentives and growing energy costs make self-supply more attractive. Car manufacturers integrate VIPV into the design of new electric models to extend range and reduce charging frequency.

The adoption rises to 30% of sales in LDV and 50% in HDV of sales in 2030.

High Uptake Plus

VIPV proves to be a strong enabler for battery electric vehicles because it offers some relief for charging anxiety that scares off some potential BEV buyers. As a result, both BEV and VIPV adoption accelerate in tandem. OEMs begin to offer VIPV as a default component in compact and mid-size electric vehicles. This leads to an increased sales of EVs in both the heavy duty and the light duty segment.

The sales shares rise to the same level as in scenario *High Uptake,* and due to the positive image of VIPV, the EV sales increase by 10%.

The uptake of EV and VIPV are shown in the following figures. Figure 111 shows the development for the light duty vehicles from 2025 to 2030. The uncertain growth beyond that is indicated by the

[50] This scenario is based on the historical and projected development of the EV fleet in the Netherlands. Source: https://publications.tno.nl/publication/34643639/KXyfPIuV/gijlswijk-2024-solarmoves.pdf

arrow. For the light duty vehicles, the uptake is relatively limited until 2030. In the scenario Low Uptake, there are 0.7 million EVs with VIPV in 2030. In scenario High Uptake and high Uptake PLUS there are 3.6 and 4 million cars in 2030.

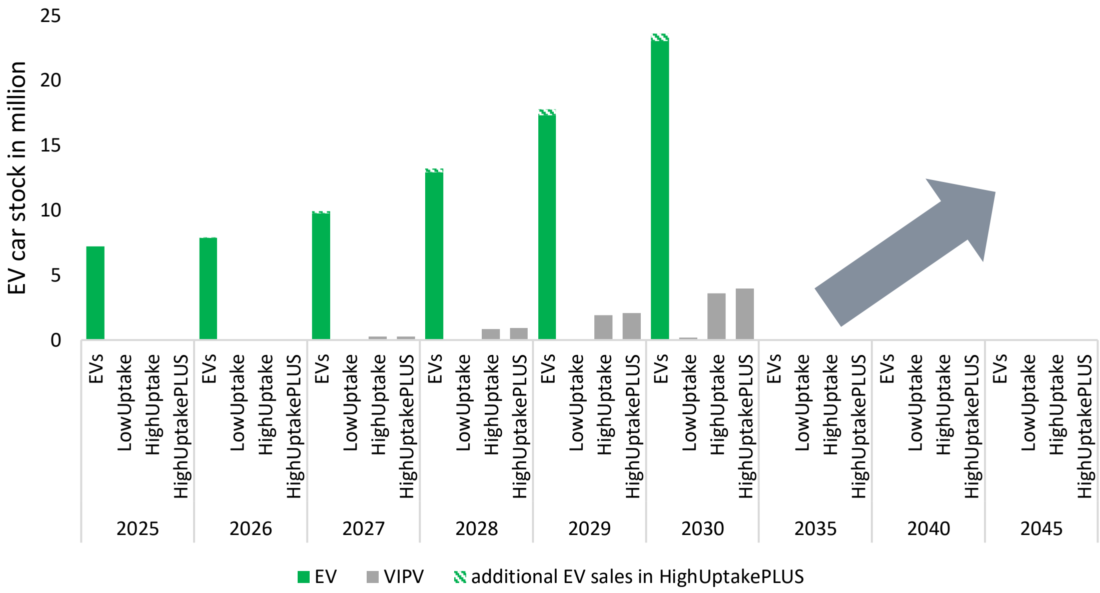


Figure 111: Development of the EV and VIPV fleet in LDV

Figure 112 shows the development of the heavy duty vehicles. In 2030 there are about 290,000 HDV in Europe. Here the scenarios developments are more similar than in the light duty segment. In 2030 there are 46,000, 80,000 and 88,000 vehicles with VIPV in the scenarios Low Uptake, High Uptake and High Uptake PLUS. These scenarios provide the adoption levels needed to quantify how VIPV shifts costs, revenues, and externalities across stakeholders.

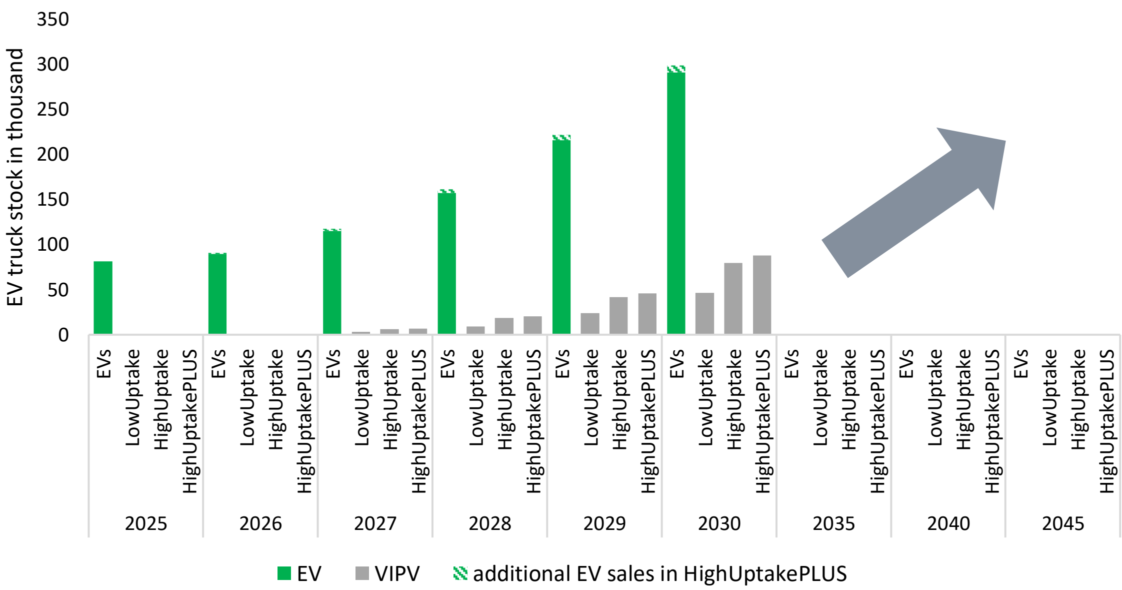


Figure 112: Development of the EV and VIPV fleet in heavy duty vehicles

3.4 Determination of costs and benefits

In Chapter 1, the Total Cost of Ownership (TCO) of VIPV vehicle owners has been calculated. Using this as a starting point, in this Chapter a broader perspective on the costs and benefits for each stakeholder was determined.

First, additional financial parameters were calculated. For the vehicle owners the payback period was added as a different perspective on the financial benefit of VIPV. For the other stakeholders the delta in revenues and investments was calculated based on the different adoption scenarios from Paragraph 3.3.2.

Drawing from the interviews, additional benefits of VIPV were identified that may influence its production or adoption. In the valuation and quantifications steps of the Value Case Methodology these benefits were rated for the applicable stakeholders (see Paragraph 3.4.1). All factors that are considered in the cost-benefit analysis are listed in the table below.

Table 46: List of factors considered in the cost and benefit analysis

Factor	Description	Applicable to stakeholders
Total Cost of Ownership (TCO)	Overall vehicle costs over 5 years, incl. CAPEX and OPEX (consisting of energy costs, maintenance costs, taxes and insurance costs)	Vehicle owners
Payback period	Number of years in which the upfront additional CAPEX for VIPV is earned back with the reduction in OPEX	Vehicle owners
Revenues (increase or decrease)	Impact on revenue streams	Charging Point Operator, Energy Company, Car Manufacturer, Solar Solution Manufacturer
Reduced investments in infrastructure	Potential savings or delays in charging/grid infrastructure investments	Grid Operator, Charging Point Operator
Emission reduction	CO_2 emissions avoided due to lower grid consumption	Vehicle owners, Policy Maker
Autonomy	Increased operational independence from charging stations	Vehicle owners
Convenience	User experience benefits through reduced charging moments	Vehicle owners
Reduced grid utilisation	Lower electricity demand on local grids, reducing congestion risk.	Grid Operator
Range Extension	Extended driving range due to VIPV-generated electricity	Vehicle owners
Brand image	Perceived innovation and sustainability of car manufacturers	Car Manufacturer, Solar Solutions Manufacturer
Increased battery lifetime	Extended lifespan due to optimization of battery operations	Vehicle owners
Noise reduction / comfort	Comfort improvements from powering auxiliary systems without idling engines	Vehicle owners (only for trucks)

Factor	Description	Applicable to stakeholders
Eco-friendly image of the vehicle	Positive image among customers or passengers due to low-carbon technology	Vehicle owners
Parking location independency	Flexibility to park without direct charging access	Vehicle owners
Regulatory compliance	Contribution to meeting regulatory standards or targets	Car Manufacturer

Note that the TCO for each archetype was calculated in Chapter 1 of Solar Moves. Where calculations were made to quantify the other factors, these were based on the same assumptions and inputs as the TCO calculations. The following section translates these factors into quantified outputs where possible and applies a transparent qualitative scoring where robust monetisation is not feasible.

Valuation & analysis of costs and benefits

This paragraph presents and analyses the valuation of the identified costs and benefits (see paragraph 3.4) from the perspective of the stakeholders in the value network of VIPV.

Scope

The geographical scope is Europe in general. However, some factors rely on quantitative inputs from Chapter 1, where results were modelled for two locations: Amsterdam and Madrid. To ensure consistency across all inputs for this valuation, Amsterdam was selected as a reference. As a result, certain effects, such as reduction in charging moments, may be conservative, since locations with higher solar irradiance (as Madrid) could show stronger impacts. Only PV integrated on the vehicle roof is considered (i.e. PV on top), PV on the sides is excluded from the assessment.

Costs and benefits are evaluated for the same time horizons used in Chapter 1 of the project: 2023 (base case), 2025, 2030, and the *Ultimate*[51] scenario. This paragraph presents and analyses the results for 2030 and discusses how these outcomes shift in the Ultimate case. Results for the remaining years are provided in Appendix N.

Stakeholder perspectives

Two stakeholder categories are identified: 1) stakeholders impacted through vehicle use (vehicle owners) and 2) stakeholders impacted through fleet-level developments. For these fleet-level stakeholders, the effects of VIPV depend strongly on the adoption level of VIPV in the total fleet. Therefore, different adoption scenarios as identified in paragraph 3.3 are evaluated.

The relevant costs and benefits differ per stakeholder. For example, vehicle owners reap benefits related to the use of a vehicle, such as increased autonomy or reduced TCO. Policymakers, on the other hand, are affected by changes in the European fleet, such as reduced emissions. Only the relevant costs and benefits are evaluated for each stakeholder. As a consequence, they vary per stakeholder.

[51] The Ultimate case is a long-term case where vehicles have higher energy efficiency, use advanced technologies, and the electricity mix has a larger share of renewable energy sources. For more details on what this case entails, see paragraph 3.4.3.

Valuation approach

Where sufficient data was available, costs and benefits are quantified. This counts for the factors *TCO*, *Payback period, CO_2 emissions* and *Convenience.* These factors were quantified in Chapter 1.

For several costs and benefits, especially those with a more behavioural nature, no reliable, consistent publicly available quantification methodology currently exists. For these factors, a qualitative assessment was applied based on expert opinion of the consortium and modelling outputs of tasks 1. The assessment uses a scoring scale from 0 to 2, where 0 represents limited or negligible benefit, 1 a moderate benefit and 2 a high benefit. A detailed description of both quantitative and qualitative scoring rationale and assumptions per factor is provided in Appendix N3 and N4, respectively.

Legend for Table 47 -

Table 57**:** Certain factors are quantified, while others are scored qualitatively on a 0-2 scale, where 0 = limited to negligible, 1 = moderate, and 2 = high benefit. A colour coding is applied:

■ highlights the highest benefit, ■ indicates a moderate benefit, □ reflects no or negligible

3.4.1. Stakeholders impacted through vehicle use (2030)

First, general results that are applicable to all vehicle archetypes are presented. This is followed by a vehicle-type-specific evaluation for each archetype group: passenger vehicles, vans, buses, and trucks.

General results (applicable to all vehicle owners)

Across nearly all vehicle archetypes, adopting VIPV can lead to a reduction in TCO in 2030, assuming a cost reduction in purchase costs of the technology over time. Within a vehicle archetype group, e.g. passenger vehicles, high mileage vehicles experience a larger absolute reduction in TCO compared to lower mileage vehicles.

The opposite is true for qualitative benefits. These are experienced more strongly by vehicle archetypes with low annual mileage and low average driving speeds. This counts especially for passenger vehicles with these characteristics. For these vehicles, the relatively low total energy demand means that VIPV can supply a substantial share of the required electricity, resulting in fewer charging moments and lower dependence on external power sources. This has a positive effect on benefits related to the use of the vehicle, such as *Convenience*, *Autonomy* and *Parking Location Independency*.

Certain qualitative factors receive the same score across all archetypes, namely *Range, Battery lifetime* and *Eco-friendly image*. The effect of these factors is not dependent on the usage or type of the vehicle, hence, they are scored uniformly across all vehicle archetypes.

Range

A score of 0 is assigned to all vehicle archetypes, as modelling results of Chapter 1 showed that the absolute increase in driving range provided by VIPV is negligible. Due to its low peak power output, VIPV cannot meaningfully impact driving range during high-speed, long-distance trips where energy consumption is highest. As a result, VIPV does not deliver a substantial benefit in extending driving range.

Battery lifetime

A score of 0 assigned for the factor *Battery lifetime* in 2030. In 2030, it is assumed that no advanced Battery Management Systems (BMS) that can optimise charging based on VIPV input is implemented. In the *Ultimate* case, however, it is assumed that BMS is widespread adopted, allowing VIPV to support more gradual charging and temperature control and reduce battery degradation, resulting in a score of 2.

Eco-friendly image (of the vehicle)

In 2030, a score of 2 is assigned to all vehicle archetype, as it is assumed that VIPV remains a relatively new technology with limited adoption. Hence, it can be considered a differentiator, resulting in a recognisable eco-friendly image. However, in the Ultimate Case, it is assumed that VIPV is more widespread adopted, hence it is no longer a unique differentiator, leading to a lower score (1) across all archetypes.

To conclude, although qualitative benefits play a marginal role for high mileage vehicles, the financial benefits alone could warrant the adoption of VIPV. For low mileage vehicles, total absolute *TCO* reduction is slightly lower. However, additional qualitative benefits can push the adoption of VIPV. The vehicle-type sections below show how this pattern differs by mileage and duty cycle, which largely determine the relative contribution of VIPV.

Vehicle owners of passenger vehicles (LPXX)

As discussed previously, integrating VIPV in passenger vehicles can lead to cost reductions in TCO across all vehicle archetypes. The greatest absolute cost reduction in TCO can be seen in vehicles with high annual mileage, as their higher energy demand allows more solar energy to offset external charging over time. The vehicle with highest annual mileage (LP33) shows the shortest payback period (1.7 years).

Table 47: Vehicle owners of passenger vehicles (LPXX): Valuation of costs and benefits between EV and VIPV in 2030

		Delta EV &VIPV 2030										
		LP10	LP11	LP12	LP13	LP14	LP21	LP22	LP23	LP31	LP32	LP33
		Small passenger car				*Medium sized passenger car*				*SUV*		
Factor	**Desired change**	*Occasional use*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*	*Car sharing*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*
TCO [€ / 5 y]	↓	-136	-64	-206	-480	-209	-144	-249	-464	-403	-676	-1,220
Payback period [y]	↓	3.7	4.3	3.3	2.4	3.4	3.9	3.4	2.7	2.9	2.3	1.7
CO_2 emission [%]	↓	-50%	-47%	-35%	-18%	-16%	-46%	-31%	-16%	-62%	-43%	-21%
Autonomy	↑	2	2	2	1	1	2	2	1	2	2	1
Convenience	↑	48%	43%	31%	11%	10%	47%	32%	12%	53%	41%	10%
Range	↑	0	0	0	0	0	0	0	0	0	0	0
Battery lifetime	↑	0	0	0	0	0	0	0	0	0	0	0
Eco-friendly image	↑	2	2	2	2	2	2	2	2	2	2	2
Parking location independency	↑	2	2	2	1	2	2	1	1	2	1	1

In addition to financial benefits, especially low mileage, urban vehicles reap benefits due to a decreased number of charging moments (reflecting an increase in the factor Convenience) and linked increased parking location independency and autonomy. As a result of their lower total energy consumption, the contribution of VIPV to their overall energy demand is relatively high. This leads to a substantial reduction in charging moments, which can be seen as a significant gain in convenience. For example, for archetype LP12, this means going from charging once every 9 days to once every 13 days.

This substantial reduction in charging moments also increases vehicle autonomy, as reliance on the grid decreases. Additionally, having a lower number of charging moments has a positive effect on parking location independency. When charging is less frequent, vehicles can be parked more flexibly without needing access to a charging point each time. This is particularly valuable in urban environments, where the availability of parking spots with charging points is limited.

For high mileage passenger vehicles, the qualitative benefits are less pronounced. This is primarily because their total energy demand is significantly higher, making the relative contribution of VIPV to their overall energy consumption relatively low. As a result, the number of required charging moments is not substantially affected. Consequently, the decision to adopt VIPV for high mileage vehicles relies mainly on financial considerations.

Vehicle owners of vans (LVXX)

Table 48: Vehicle owners of vans (LVXX): Valuation of costs and benefits between EV and VIPV in 2030

		Delta EV vs. VIPV 2030			
		LV11	**LV12**	**LV21**	**LV22**
		Small van		*Large van*	
Factor	**Desired change**	*Local distribution*	*Regional distribution*	*Local distribution*	*Regional distribution*
TCO [€ / 5 year]	↓	-554	-914	-732	-1210
Payback period [years]	↓	2.7	2.1	2.7	2.0
CO_2 emission [%]	↓	-21%	-18%	-16%	-22%
Autonomy	↑	1	0	0	0
Convenience	↑	14%	12%	7%	13%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

For vans, the financial benefits are present, but qualitative benefits are limited. Across all van archetypes, VIPV contributes to a reduction in TCO, with the greater absolute savings in high-mileage vehicles.

However, as vans typically have a relatively high annual mileage, their overall energy demand is substantial, making the contribution of VIPV to the total energy demand relatively small. As a result, there is not a significant reduction in charging moments (reflected as a gain in factor *Convenience).* Due to this, benefits related to the reduction in charging moments, i.e. *Autonomy*, *Convenience* and *Parking Location Dependency* receive a low score.

Vehicle owners of buses (HBXX)

Table 49: Vehicle owners of buses (HBXX): Valuation of costs and benefits between EV and VIPV in 2030

Factor	Desired change	Delta EV vs. VIPV 2030 HB11	HB12	HB22	HB23
		Low-floor bus		*High-floor bus*	
		Urban public transport service	*Peri urban public transport service*	*Regional public transport*	*Long-distance highway travel*
TCO [€ / 5 y]	↓	-505	-315	-712	-1,855
Payback period [Y]	↓	3.5	3.8	3.2	2.3
CO_2 emission [%]	↓	-1%	-2%	-2%	-1%
Autonomy	↑	0	0	0	0
Convenience	↑	0%	0%	0%	0%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

As for buses archetypes, the adoption of VIPV by bus owners would be mainly driven by financial considerations. Due to relatively high annual mileage and accompanying relatively high total energy demand, qualitative benefits are limited as the contribution of VIPV to the total energy demand is minimal.

Vehicle owners of trucks (HTXX)

For trucks archetypes, as outlined in the introduction of this chapter, two comparisons are made:

1. Internal Combustion Engine (ICE) trucks versus ICE trucks that are VIPV-equipped
2. EV Trucks versus EV trucks that are VIPV-equipped.

This distinction is made because VIPV technology is often implemented as an add-on to existing ICE trucks. This can deliver notable benefits, including reductions in operational costs and CO_2 emissions, because of lower diesel consumption.

ICE vs. VIPV-ICE

Table 50: Vehicle owners of trucks (HTXX): Valuation of costs and benefits between ICE and VIPV-ICE in 2030

Factor	Desired change	Delta ICE vs. VIPV 2030 HT11	HT12	HT22	HT23
		Rigid truck		*Tractor-trailer*	
		Urban distribution	*Regional distribution*	*Urban distribution*	*Regional distribution*
TCO [€ / 5 year]	↓	€-5,239	€-8,105	€-14,092	€-32,452
Payback period [years]	↓	1.1	1.0	1.1	0.7
CO_2 emission [%]	↓	-6.2%	-4.4%	-9.2%	-5.2%
Battery lifetime	↑	0	0	0	0
Noise reduction / comfort	↑	0	1	0	2
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

When comparing ICE trucks with ICE trucks that are VIPV-equipped, it can be concluded that adopting VIPV can result in significant TCO and emission reductions. Both absolute TCO and emission reductions are largest in high mileage vehicles, as VIPV yield can be fully implemented. Next to that, adopting VIPV in diesel trucks can bring qualitative benefits: VIPV can power auxiliary systems such as cooling or refrigeration, so that the engine does not have to idle during break or overnight rest. This reduces fuel use and increases comfort for the driver by lowering noise levels.

EV vs. VIPV

Table 51: Vehicle owners of trucks (HTXX): Valuation of costs and benefits between EV and VIPV in 2030

		Delta EV vs. VIPV 2030			
		HT11	HT12	HT22	HT23
		Rigid truck		*Tractor-trailer*	
Factor	**Desired change**	*Urban distribution*	*Regional distribution*	*Regional distribution*	*Long-haul freight transport*
TCO [€ / 5 year]	↓	€123	€-242	€51	€-4,591
Payback period	↓	>5	4.6	>5	2.8
CO_2 emission [%]	↓	-6%	-5%	-7%	-3%
Autonomy	↑	0	0	0	0
Convenience	↑	0%	0%	0%	0%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

Whereas integrating VIPV in ICE trucks can lead to significant cost reductions within the 5-year horizon of the TCO calculations, the financial benefits are less pronounced in VIPV-equipped EV trucks. Two (HT12 and HT23) of the four archetypes show a TCO reduction within 5 years. In addition, the relatively high annual mileage of trucks, and the corresponding high total energy demand, means that the contribution of VIPV to overall energy use is small, resulting in limited qualitative benefits of VIPV. While the previous results capture benefits at the level of the individual user, several impacts only emerge at scale. The analysis therefore shifts to fleet-level stakeholders, where effects depend on aggregate adoption levels rather than single-vehicle performance.

3.4.2. Stakeholders impacted through fleet-level developments

In this paragraph, costs and benefits will be evaluated for stakeholders that are affected by changes in the European fleet because of VIPV adoption, rather than the individual use of the vehicle − in the case of vehicle owners. For these stakeholders (referred to as *fleet-level stakeholders*), the effect of VIPV is dependent on the level of uptake. Therefore, costs and benefits for each stakeholder are evaluated across the four different scenarios:

1. **Base**: no uptake of VIPV
2. **Low Uptake**: limited uptake of VIPV
3. **High Uptake**: relatively high uptake of VIPV
4. **High Uptake Plus**: relatively high uptake of VIPV combined with accelerated uptake of EVs

For a more detailed description of scenarios, please refer to paragraph 3.3.

Policymaker

Table 52: Policymakers: Valuation of costs and benefits across different VIPV adoption scenarios in 2030 per scenario

Scenario		CO$_2$ Reduction (% of total EU road emissions in 2022)[52]
Name	**Description**	**2030**
Base	No uptake of VIPV	0%
Low Uptake	Low uptake of VIPV	0.01%
High Uptake	High uptake of VIPV	0.07%
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	0.07%

For policymakers, an important factor to consider is potential CO$_2$ reduction resulting from the adoption of VIPV. Electricity generated through VIPV and consumed by the vehicle will not have to be charged from external sources, in this case the electricity grid. While the EU aims to achieve a low-carbon electricity mix by 2050, the current electricity mix is still partly reliant on fossil-fuelled generation. This will likely remain true – albeit at a lower intensity – in 2030. As VIPV provides fully renewable electricity, reducing electricity consumption from the grid can lead to lower emissions.

To quantify the potential emission reduction, for each scenario in 2030, the potential reduction is calculated as a percentage of total EU road transport emissions in 2022, which serves as reference point. The results presented in Table 52 show that VIPV's contribution to overall transport emission reduction in the EU is minimal (<1%).

It should be noted that this analysis does not include two factors that would increase the total emission reduction as a result of VIPV adoption. First, the potential emission reduction from VIPV integrated in ICE trucks is excluded, as this analysis compares a fleet of EVs with and without VIPV. The previous valuation of costs and benefits for the ICE trucks with and without VIPV – paragraph *Vehicle owners of trucks (HTXX)* – indicates that integrating VIPV could result in an emission reduction of ~5% per ICE truck. Second, for the *High Uptake Plus* scenario, where VIPV accelerates EV uptake, only the emission reduction directly attributable to VIPV is considered. The additional reduction from replacing ICE vehicles with EVs as a result of VIPV-induced uptake is not included in this analysis. Including both effects would therefore lead to a higher overall emission reduction than presented in Table 52.

Grid Operator

Table 53: Grid Operators: Valuation of costs and benefits across different VIPV adoption scenarios in 2030

Scenario		Grid Utilisation	Investment in Infrastructure
Name	**Description**	**2030**	**2030**
Base	No uptake of VIPV	0	0
Low Uptake	Low uptake of VIPV	1	1
High Uptake	High uptake of VIPV	2	2
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	1	1

Relevant factors for the Grid Operator are (reduced) *Grid utilisation* and (reduced) *Investment in infrastructure*. VIPV provides electricity directly to the vehicle, reducing its reliance on the grid for

[52] Emission reductions shown exclude effects from integrating VIPV in ICE trucks and accelerated EV uptake in *High Uptake Plus* scenario.

electricity provision. As VIPV provides part of the total electricity demand of the vehicle, there is an increased flexibility in the timing of charging moments, resulting in a different distribution of charging moments over time. Therefore, VIPV reduces grid utilisation by EVs and may potentially also lead to a reduction in peak demand, partly alleviating local grid congestion.

As a result, VIPV adoption can positively impact (i.e. reduces) grid utilisation and may defer or reduce infrastructure investments through a lower peak demand. The magnitude of both effects depends on the level of adoption: the higher the number of VIPV-equipped vehicles, the larger the benefit. Thus, in the scenario with high adoption (*High Uptake* scenario), these benefits are most pronounced, resulting in the highest score (2) for both factors. However, in the other scenario with high adoption – the *High Uptake Plus* scenario, the adoption of EVs is accelerated through VIPV, thereby cancelling out the reduction in grid utilisation (and therewith the reduced or deferred investments in infrastructure) as the EV fleet is larger.

Charging Point Operator (CPO)

Table 54: Charging Point Operator (CPO): Valuation of costs and benefits across different VIPV adoption scenarios in 2030

Scenario		Revenues [€/y]	Investment in Infrastructure (0-2)
Name	**Description**	**2030**	**2030**
Base	No uptake of VIPV	€0	0
Low Uptake	Low uptake of VIPV	-€54 million	0
High Uptake	High uptake of VIPV	-€533 million	0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	-€569 million	0

Relevant factors for the CPO are the (loss of) *Revenues* and (reduced) *Investments in infrastructure*. As VIPV provides part of the vehicle's total electricity demand, electricity consumption for the grid decreases, leading to a reduction in charging-related revenues for the CPO (in the street and at fast charging locations). The higher the uptake of VIPV, the larger the reduction in revenues due to reduced charging infrastructure utilisation (see Table 54).

Although it may seem that VIPV could reduce the need for charging infrastructure investments by lower utilisation, its actual impact is limited because benefits are seasonal. While VIPV can lower charging demand during summer, its effect is negligible in winter and minimal at the system level, making it an insufficient driver to significantly reduce the needed charging infrastructure capacity.

Energy Company

Table 55: Energy Company: Valuation of costs and benefits across different VIPV adoption scenarios in 2030

Scenario		Revenues [€/y]
Name	**Description**	**2030**
Base	No uptake of VIPV	€0
Low Uptake	Low uptake of VIPV	-€88 million
High Uptake	High uptake of VIPV	-€858 million
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	-€917 million

Similar to the revenue decline for CPOs, energy companies also face reduced revenues due to lower charging at home. As VIPV provides part of the electricity demand of the vehicle, less electricity is consumed from home charging points. This decreases consumption from the electricity grid, leading to lower electricity sales, thereby negatively impacting revenues of energy companies.

Again, the loss of revenues correlates positively with the uptake of VIPV: the higher the adoption rate, the greater the reduction in electricity consumption from the grid, and consequently, the larger the revenue loss for energy companies. Accordingly, scenarios with high uptake – High Uptake (Plus) - show a larger reduction in revenues (see Table 55).

Solar Solution Manufacturer

The solar solution manufacturer benefits from additional revenues through the sale of VIPV systems to OEMs, who integrate the technology into new vehicle models. The additional revenues correlate with the uptake of VIPV in the market. Sales numbers of VIPV are tied to adoption levels, therefore higher adoption levels lead to higher revenues, as can be seen in Table 56.

Table 56: Solar Solution Manufacturer: Valuation of costs and benefits across different VIPV adoption scenarios in 2030

Scenario		Revenues [€/y]
Name	**Description**	**2030**
Base	No uptake of VIPV	€0
Low Uptake	Low uptake of VIPV	+€418 million
High Uptake	High uptake of VIPV	+€1,645 million
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	+€1,784 million

OEM / Car manufacturer

Relevant benefits for the OEMs and Car manufacturers are *Revenues, Brand Image* and *Regulatory Compliance.*

For OEMs and car manufacturers, additional revenues arise from providing VIPV as a feature to vehicles in their portfolio. It is assumed that they will apply a markup to the base cost of the VIPV system purchased from the solar solution manufacturer. Consequently, OEMs can generate additional revenues per VIPV-equipped vehicle sold. The amount of additional revenues correlates with the adoption levels of VIPV: higher adoption leads to greater additional revenues (see

Table 57).

In addition to the direct financial gain, VIPV integration can also strengthen the manufacturer's brand image as the technology demonstrates innovation and sustainability leadership. To differentiate the brand, sales volumes of VIPV-equipped vehicles must be significant. Therefore, only a positive score (>0) is assigned to scenarios *High Uptake* and *High Uptake Plus*.

Lastly, regulatory compliance is an important consideration for manufacturers, who are held accountable for meeting emission reduction targets under Regulation (EU) 2019/631 and Regulation (EU) 2019/1242. However, VIPV does not provide any recognised reduction in emissions compared to EVs, which already have zero tailpipe emissions. As a result, VIPV does not contribute to compliance of regulatory targets, so a score of zero is applied across all scenarios – except in the *High Uptake Plus* scenario, where VIPV is assumed to accelerate EV adoption and thereby reduce penalty exposure for manufacturers. In this case, a score of 2 is assigned (see Table 57).

Table 57: OEM / Car Manufacturer: Valuation of costs and benefits across different VIPV adoption scenarios in 2030

Scenario		Revenues [€/y]	Brand Image [0-2]	Regulatory Compliance [0-2]
Name	**Description**	**2030**	**2030**	**2030**
Base	No uptake of VIPV	€0	0	0
Low Uptake	Low uptake of VIPV	+€1,209 million	0	0
High Uptake	High uptake of VIPV	+€2,742 million	2	0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	+€2,973 million	2	2

3.4.3. Ultimate case

In previous paragraphs, costs and benefits are evaluated per stakeholder for 2030. In addition to the 2030 assessment, a theoretical *Ultimate* case is included to explore the potential of VIPV in the long-term. In this paragraph, it is evaluated how the valuation of costs and benefits changes in the *Ultimate* case compared to the 2030 assessment (Table 58).

The *Ultimate* case is not tied to a specific timeframe, but provides a long-term perspective in which vehicle have significant higher energy efficiency, and other technological improvements, such as advanced battery management systems and smart charging, are in place. This case also assumes that the share of renewable energy sources in the electricity mix is higher, as aligned with long-term European emission targets. For the *Ultimate* case, a combination of energy-reduction measures has been assumed to be implemented, aligned with the approach in Chapter 1, including options that may not be economically viable today.

Table 58: Comparison of costs and benefits per stakeholder category between the 2030 and the Ultimate case, illustrating how the potential impact of VIPV changes over the long-term

		Delta EV vs. VIPV	
Stake-holders	**Factor**	**Change (2030 → Ultimate)**	**Description**
Vehicle owners (LPXX, LVXX, HBXX, HTXX)	TCO	▼	Greater reduction in TCO due to improved vehicle energy efficiency
	CO_2 emission	▲	Growing share of renewables in the grid reduces the relative emission benefit of VIPV
	Autonomy	■	No change
	Convenience	▲	Higher efficiency leads to lower energy demand and hence a lower amount of needed charging moments
	Range	■	No change
	Battery Lifetime	▲	Improved battery life through advanced BMS implementation
	Eco-friendly image	▼	Widespread adoption makes it less of a differentiator
	Parking location independency	■	No change
Fleet-level stake-holders	CO2 emissions	▲	Growing share of renewables in the grid reduces the relative emission benefit of VIPV
	Revenues	▲ / ▼	Depends on stakeholder. Higher adoption rates of VIPV lead to stronger revenue losses or gains respectively of the stakeholder
	Grid utilisation	▼	Impact of VIPV lessened by widespread smart charging adoption
	Investments in electricity grid infrastructure	▼	Widespread smart charging adoption reduces VIPV's role in lowering infrastructure investments
	Investments in charging infrastructure	■	No change
	Brand image (OEM / car manufacturer)	▼	More widespread VIPV adoption means it is no longer a key differentiator
	Regulatory compliance	■	No change

The effect of taking this long-term perspective differs per stakeholder group. For vehicle owners, the increased energy efficiency of the vehicles reduces overall electricity consumption, resulting in a larger relative contribution of VIPV to total demand. This higher efficiency also leads to a reduction in charging moments, which results in an additional 8% reduction as calculated in Chapter 1. Benefits of other factors, such as autonomy and parking-location independence, remain largely unchanged, and convenience-related aspects show only minimal differences.

For fleet-level stakeholders, the benefits of VIPV in reducing grid utilisation and lowering related infrastructure investments are lower. With the assumed widespread adoption of smart charging, lowering peak demand through optimal selection of charging moments can alleviate grid stress, limiting the incremental contribution of VIPV. Next to that, due to the assumed increase in the share of renewable energy sources in the electricity mix, the impact of VIPV on emission reduction becomes less as the emission-intensity of the grid reduces. These trends suggest that while VIPV can still provide value, its relative impact at the fleet level is smaller in a future scenario with widespread adoption of smart charging and a low-carbon electricity system.

3.4.4. Conclusion

This chapter has expanded on the TCO calculations performed in Chapter 1 and evaluated the broader costs and benefits of VIPV across different vehicle archetypes and stakeholder groups for 2030, as well as in a long-term *Ultimate* case. The main conclusions are presented below.

Light duty vehicles (LPXX and LVXX)

In 2030, VIPV leads to a reduction in TCO across all archetypes and a payback period <5 years, with shorter payback periods for high mileage vehicles. For low mileage vehicles, additional benefits related to the use of the vehicle have been identified, particularly regarding the reduction in charging moments. The value network analysis highlights that successful adoption of VIPV depends on consumers perceiving that these benefits outweigh the additional upfront capital costs. Furthermore, OEMs and car manufacturers can act as gatekeepers: end-consumers can only adopt VIPV if manufacturers choose to integrate it into vehicles. Policymakers on their part can have direct influence on manufacturers, e.g. by imposing emission reduction targets on new vehicles and including VIPV as a reduction measure.

Heavy duty vehicles (HBXX and HTXX)

For heavy duty vehicles, a distinction must be made between buses, ICE trucks and EV trucks. For buses, the decision to implement VIPV is primarily financial with payback periods well below 5 years. ICE trucks equipped with VIPV benefit by running their auxiliary systems on green rather than diesel generated electricity. This leads to significant cost reductions, with payback periods around one year across all archetypes, and additional non-financial benefits in emission and noise reduction. For EV trucks the decision to adopt VIPV is primarily a financial consideration, with payback periods <5 years for the long-haul archetypes.

Stimulating adoption in this segment might pose a challenge, since policy leverage is limited: emission reduction targets apply to manufacturers rather than fleet operators, which are the end-consumers of the VIPV technology.

Societal impacts (from fleet-level stakeholders)

At the fleet level, the comparison between EVs with and without VIPV shows limited benefits in terms of CO_2 emission reduction. If VIPV can accelerate the widespread adoption of EVs (as in the *High Uptake Plus* scenario), the short-term impact is more measurable. The impact of VIPV on grid utilisation (particularly through reducing peak demand) is also uncertain. Although VIPV is expected to have a positive effect, as it enhances charging moment flexibility, it is uncertain how substantial this effect is and to what extent smart charging alone could result in similar outcomes. With widespread VIPV adoption, revenue streams shift from grid-related stakeholders towards the automotive (including VIPV) industry, as electricity consumption from the grid reduces while sales of VIPV products increases.

Overall, the policy measures proposed in paragraph 3.5 aim to address these challenges and better align incentives across the value network, supporting more effective VIPV adoption.

3.5 Policy aspects

This paragraph outlines the policy landscape relevant to VIPV and formulates recommendations for policy measures to stimulate the adoption of VIPV. It first reviews existing EU regulations (3.5.1), then identifies key barriers and accelerators that may hamper, delay or on the other hand accelerate the adoption of VIPV and finally offers recommendations for policy measures (3.7).

3.5.1. Relevant policy regulations and initiatives

The following policy regulations and initiatives have been identified and considered in the formulation of the recommendations for policy measures. We refer to Appendix O for the introductory texts on each regulation published by the EU.

Fit for 55

The Fit for 55 package is the EU's flagship climate policy framework, designed to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. It includes a broad range of measures across all sectors, including transport. Within transport, light and heavy duty vehicles are regulated under separate CO_2 emission performance standards. These regulations shape the enabling environment for VIPV adoption.

In the context of this research, we would like to highlight the following relevant components:

- *Light-duty vehicles* - the aim is to achieve a zero-emission target on new vehicles sold from 2035 onward.
- *Heavy-duty vehicles* - several targets are in place, specifically a CO_2 emission reduction path for emissions across all vehicles manufactured by a company, with a target of -65% in 2035, and a requirement for all new city buses to be zero-emission by 2035.
- *VECTO* - the Vehicle Energy Consumption calculation TOol (VECTO) is the tool that is used to determine CO_2 emissions and fuel consumption from heavy-duty vehicles. For this VIPV study, two modules of VECTO are relevant: VECTO Engine and VECTO Trailer. Currently, VIPV is not included as a CO_2 reduction measure in either module. However, the VECTO Trailer module is undergoing a revision process. As part of this, an external advisory group has proposed the inclusion of solar (VIPV) systems on semi-trailers as a recognised

method to reduce emissions from HDVs for the coming period. A formal decision on this proposal is expected in Q1 2026.

- *AFIR* - the Alternative Fuels Infrastructure Regulation (AFIR) sets mandatory national targets for the deployment of alternative fuels infrastructure in the EU, among others for road vehicles. VIPV aims for the same goal, i.e. to provide clean energy and to make it readily available for vehicles.

Net-Zero Industry Act

The Net-Zero Industry Act aims to increase the EU's manufacturing capacity of technologies that support the clean energy transition. VIPV poses an opportunity both for manufacturers of the technology itself, and for car manufacturers to play a leading role in the worldwide energy transition.

EU Competitiveness Compass

Building on the Draghi report on the future of European competitiveness, the EU Competitiveness Compass aims to boost technological innovation, reduce carbon emissions and diversify and strengthen EU supply chains, especially regarding critical sectors and technologies. As with the Net-Zero Industry Act, VIPV is one of the innovative technologies that fits all these goals.

3.6 Barriers and accelerators for VIPV adoption

As a preliminary step towards policy recommendations, barriers and accelerators for the adoption of VIPV have been identified. These barriers and accelerators have been grouped into general factors (applicable to both light and heavy duty vehicles), and vehicle-segment specific factors for light duty and heavy duty vehicles. First the barriers are presented, followed by the accelerators.

3.6.1. Barriers that may hinder the adoption of VIPV

General barriers

These barriers apply across vehicle segments and reflect barriers that may hamper the adoption of VIPV in the market, regulatory environment, and ecosystem. The barriers are grouped by category.

Barriers		
Financial	GB.1	Long payback period for end-users limits market penetration
	GB.2	OEMs perceive VIPV as costly
	GB.3	Limited cost-effectiveness of VIPV
Regulatory	GB.4	No regulatory framework for VIPV
	GB.5	Lack of standards for solar integration in vehicles
	GB.6	Safety concerns for VIPV on roads
	GB.7	Delay in implementation of Corporate Sustainability Reporting Directive (CSRD)[53] affects sustainability incentives
Eco-system	GB.8	Solar technology has shorter innovation cycles compared to automotive resulting in a mismatch
	GB.9	Shortage of skilled technical workforce in EU
	GB.10	No established solar supply chain in EU
	GB.11	Dependence on solar panel imports
	GB.12	Automotive industry is risk-averse and conservative

[53] Directive (EU) 2022/2464, http://data.europa.eu/eli/dir/2022/2464

Customer awareness & perception	GB.13	Customers are unaware that behaviour change is needed to maximise VIPV benefits
	GB.14	OEMs lack understanding of VIPV potential
	GB.15	Customer behaviour limits VIPV effectiveness
	GB.16	Perception that ICE vehicles will still be available in the mid-term
	GB.17	Concerns about seasonal & geographical fluctuations
	GB.18	Perception that VIPV generates insufficient electricity
	GB.19	General public scepticism about VIPV
Technical	GB.20	VIPV cannot provide full grid independence

Light Duty-specific barriers

In addition to the general barriers, light-duty vehicles face specific challenges due to their design and regulatory constraints.

Barriers		
Financial	LDB.1	Potential for low update levels if offered as an option for consumers undermines required investments by OEMs
Regulatory	LDB.2	End-of-Life Directive restricts the use of lead in VIPV
	LDB.3	VIPV on LDVs requires additional testing during homologation
Eco-system	LDB.4	Lack of knowledge how to market and sell vehicles with VIPV
Technical	LDB.5	Limited surface area on passenger cars reduces potential VIPV yield

Heavy Duty-specific barriers

Heavy-duty vehicles encounter unique barriers related to ownership structures, technical compatibility, and financial incentives.

Barriers		
Financial	HDB.1	Trailer–tractor ownership mismatch: when tractors and trailers have different owners, VIPV costs and benefits may be unevenly distributed
	HDB.2	Payback time of VIPV exceeds acceptable threshold in transport market
Regulatory	HDB.3	No standardised high-voltage electrical interface between tractor and trailer in the EU
Customer awareness & perception	HDB.4	Limited customer awareness and knowledge of VIPV
Technical	HDB.5	Tractor and trailer often from different manufacturers resulting in incompatible systems

3.6.2. Accelerators that may stimulate the adoption of VIPV

General accelerators

These accelerators apply broadly across vehicle segments and reflect factors that may stimulate the adoption of VIPV.

Accelerators		
Strategic Autonomy	GA.1	Increased battery lifetime resulting in higher resource efficiency
Knowledge Development	GA.2	Availability of data on VIPV in use cases
	GA.3	Scientific evidence on VIPV’s added value
	GA.4	Clear identification of the non-monetary benefits of VIPV and communication/marketing to customers and fleet operators
	GA.5	First mover advantage in the automotive industry

European Compete-tiveness	GA.6	VIPV as differentiator for EU automotive industry
Regulatory Incentives	GA.7	EU emission targets creating regulatory pressure for low-emission vehicles
	GA.8	Public procurement stimulating new technologies as VIPV
Technical	GA.9	Smart charging integration to maximise use of VIPV-generated energy
	GA.10	Gamification encourages customer behaviour that improves VIPV yield
	GA.11	Bi-directional charging allows VIPV vehicles to supply power when parked, increasing utilisation and value
	GA.12	VIPV integration improves vehicle energy efficiency gains

Light Duty-specific accelerators

Light-duty vehicles benefit from targeted regulatory and design-related accelerators.

Accelerators		
Regulatory Incentives	LDA.1	Regulation (EU) 2019/631 sets CO_2 emission performance standards for manufacturers of light duty vehicles
Technical	LDA.2	Aesthetic integration of VIPV in passenger cars
	LDA.3	Availability of a glass-free option that passes homologation and fits with PFAS-free

Heavy Duty-specific accelerators

Heavy-duty vehicles are supported by specific regulatory and ecosystem-based enablers.

Barriers		
Regulatory Incentives	HDA.1	Regulation (EU) 2019/1242 sets CO_2 emission performance standards for manufacturers of heavy duty vehicles
Technical	HBA.2	Availability of solar optimal routing functionality in route planning tools

3.7 Policy recommendations

The following policy recommendations have been identified. Indicated for each main category are the barriers and accelerators that are targeted. Note that not all barriers and accelerators can be targeted with policy or regulations.

Another important note is that the emission reduction achieved by VIPV should not be double counted. Some of the policy recommendations presented in this chapter could, if implemented together, lead to overlapping or double-counted benefits. Therefore, these recommendations are presented as potential options to support the adoption of VIPV, rather than as a prescriptive or cumulative set of measures.

1. Participate in creating a narrative for VIPV

Targeted barriers: Regulatory (GB.6), Customer Awareness & Perception (GB.13, GB.14, GB.15, GB.16, GB.17, GB.18, GB.19, HBD.5), Technical (GB.20)
Targeted accelerators: Knowledge Development (GA.2, GA.3, GA.4)

From an awareness perspective and to counter misinformation, the EU and member states could take an active role in informing the general public on sustainable transport developments such as VIPV.

1.1. Increase availability of fact-based information - Fund research and pilots aimed at collecting data and building knowledge on the use of VIPV and its applications.
1.2. Increase public awareness - Subsequently, make the information collected widely and publicly available to help increase public awareness. Experiences from existing VIPV end-users could be used in addition.
1.3. Communicate CO_2 abatement costs transparently – develop and publish CO_2 abatement costs of VIPV. Transparent benchmarking of VIPV with other emission-reduction technologies can help policymakers and industry to recognise relative cost-effectiveness of decarbonisation options.

2. <u>Offer financial incentives to VIPV owners and end-users</u>

Targeted barriers: Financial (GB.1, GB.3, HDB.2)
Targeted accelerators: -

The analyses in paragraph 3.4 shows that the business case for VIPV, given assumptions on (amongst others) cost and pricing developments, PV yield improvement and vehicle efficiency improvements, could be positive by 2030 for nearly all vehicle archetypes. Given a positive business case, there may still be a rationale for providing financial incentives to (potential) VIPV owners and end-users. One reason may be that they could stimulate the early adoption of VIPV, similar to incentives that have been widespread across Europe to stimulate the adoption of PV on buildings. Financial incentives may be aimed at reducing risks (i.e., reducing dependency on market prices for energy) or shortening the pay-back time.

Proposed policy measures include:

2.1. Tax incentives - e.g. through differentiation in road taxes. Similar policies have been or still are in place for EVs, where the adoption has unmistakably been stimulated by tax benefits.
2.2. Subsidies - e.g. by including VIPV equipped vehicles in existing subsidy mechanisms to stimulate consumers adopting sustainability measures.

3. <u>Stimulate European automotive industry to offer VIPV</u>

Targeted barriers: Financial (GB.2, HDB.1), Regulatory (GB.4, GB.5), Customer Awareness & Perception (HDB.4)
Targeted accelerators: Strategic Autonomy (GA.1), European Competitiveness (GA.5, GA.6), Regulatory Incentives (LDA.1, HDA.1)

As indicated in paragraph 3.5.1, the automotive industry faces requirements on reducing emissions from new vehicles. VIPV could contribute to this reduction, but faces a number of barriers for industry to adopt this technology as described in paragraph 3.6.

Proposed policy measures to take away these barriers are:

3.1. Build a regulatory framework for VIPV - Provide definitions and assumptions at EU-level to provide clarity and a level playing field. This would include a definition of solar mobility (i.e. VIPV, VAPV) per archetype at EU & member state level, including:
   - Adjust definition based on use: propulsion vs. auxiliary systems
   - Minimum entry requirement, i.e. X kWp or percentage of the area

3.2. Establish homologation guidelines - Develop EU-wide homologation guidelines to integrate VIPV into the existing vehicle type-approval framework (Regulation (EU) 2018/858).
3.3. Include VIPV in VECTO Trailer - Include VIPV as a recognised technology option within the VECTO Trailer simulation tool, enabling the energy contribution of VIPV to be quantified and counted as certified CO_2 emission reductions.
3.4. Stimulate vehicle efficiency, including VIPV – Establish policies and incentive schemes that promote vehicle efficiency measures in general, of which VIPV integration can be a recognised option as a complementary measure that improves external efficiency by reducing reliance on external charging. Improved vehicle efficiency reduces overall energy demand, thereby increasing the proportion of total energy supplied by VIPV.

4. Recognise VIPV as sustainable measure

Targeted barriers: Eco-system (GB.8, GB.12), Customer Awareness & Perception (GB.14, GB.16)
Targeted accelerators: Regulatory Incentives (GA.7, LDA.1, HDA.1)

VIPV is a relatively new technology that is not (yet) recognised and incorporated in policy and regulations targeting decarbonisation of mobility. Inclusion in such policy and regulations could stimulate the production and adoption of VIPV.

4.1. Classify electricity generated through VIPV as renewable energy
Under RED III, the EU sets binding renewable energy targets for all sectors, including transport. Electricity generated by VIPV is not yet clearly recognised as renewable energy, so its contribution may go uncounted. During the revision of RED III or its implementing and delegated acts electricity produced by VIPV could be classified as renewable and the introduction of a dedicated certificate or accounting module would ensure VIPV-generation explicitly contributes to EU renewable energy targets.
4.2. Expand Eco-innovations to include innovations for more efficient EVs (including on-board solar)
To promote the development of new and advanced technologies reducing CO_2 emissions from vehicles and the improvement of energy efficiency, manufacturers may obtain emission credits for vehicles equipped with innovative technologies (eco-innovations) whose full CO_2 savings cannot be demonstrated during type-approval. Including VIPV in this eco-innovation scheme would encourage adoption of on-board solar systems. The full potential of VIPV specific to the vehicle should be accounted either in terms of CO_2 emissions or energy efficiency.

5. Include requirement for VIPV in government tenders

Targeted barriers: Financial (GB.2)
Targeted accelerators: European Competitiveness (GA.5, GA.6), Regulatory Incentives (GA.8)

5.1. As a direct measure, local, regional and national governments could contribute to VIPV adoption by including VIPV as a beneficial factor in tenders for e.g. bus services, the acquisition of vans, trucks and trailers or military vehicles. It has already become common practice to require buses in tenders to be battery-electric. Similarly, the use of VIPV could be incentivised or even required.

5.2. Another option would be to require or stimulate retrofitting existing government-owned or controlled buses, vans, trucks and trailers with VIPV.

3.7.1. Impact, ease of implementation and timeframe

In the table below, an indication is given of the impact of the policy recommendation on VIPV adoption, ease of implementation and timeframe for each policy recommendation.

Table 59: Overview of policy recommendations

	Recommendation	Targeted policy / regulation	Impact	Ease of implementation[54]	Timeframe[55]
1	**Participate in creating a narrative for VIPV**				
1.1	Fund fact-based information	No specific	Medium	High	Short- to long-term
1.2	Disseminate information	No specific	Medium	High	Short- to long-term
1.3	Communicate CO_2 abatement costs	No specific	Medium	High	Short- to long-term
2	**Offer financial incentives to VIPV owners and end-users**				
2.1	Tax incentives	Member state-specific	High	Medium	Mid-term
2.2	Subsidies	Member state-specific	High	Medium	Mid-term
3	**Stimulate European automotive industry to offer VIPV**				
3.1	Regulatory framework	No specific	High	Low	Mid-term
3.2	Homologation guidelines	Whole Vehicle Type-Approval System (WVTA), Regulation (EU) 2018/858	High	Low	Mid-term
3.3	Include in VECTO Trailer	VECTO Trailer	Medium	High	Short-term
3.4	Stimulate vehicle efficiency	No specific	Medium	Low	Mid- to long-term
4	**Recognize VIPV as sustainable measure**				
4.1	Define as renewable energy	REDIII	Medium		Mid-term
4.2	Expand eco-innovations	Regulation (EU) 2019/631	Medium	Medium	Mid-term
5	**Include requirement for VIPV in government tenders**				
5.1	Requirement in tenders	Member state-specific	Medium	Medium	Mid-term
5.2	Retrofit government-owned vehicles	Member state-specific	Medium	Medium	Mid-term

[54] **Ease of implementation**: *Low* means implementation is expected to be difficult or complex, whereas *High* indicates relatively easy implementation.
[55] **Timeframe**: *Shot-term* = less than 1 year, *Mid-term* = 1-5 years, *Long-term* = more than 5 years.

4. Project management, progress & deviations and dissemination

4.1 Project management

General

Whereas the contract between DG-MOVE and the consortium was signed on December 21, 2022, the project started with a kick-off meeting in Brussels on January 17, 2023. The consortium was almost immediately faced with the bankruptcy of project partner Atlas Technologies B.V.: the mother company of Lightyear, on January 26, 2026. This sad end of this project partner, however, did not have impact on planned the activities in Task 1 since the tasks of Atlas Technologies were taken over by a new consortium partner: Lightyear Layer B.V. The formal accession of Lightyear to the SolarMoves consortium was finally arranged in December 2024 by signing a formal accession agreement between DG MOVE of the European Commission, coordinator TNO, Lightyear layer BV and the curator of Atlas Technologies BV.

Another point of concern from the beginning of the project was the financial status of Sono Motors. This project partner terminated the Sion car production program in February 2023 and filed for insolvency in May. The company since then focusses on Solar Business for B2B Customers. On 27 November 2023 Sono Motors, announced "the signing of investment agreements with YA II PN, Ltd. ("Yorkville"), which are expected to enable the company to restructure itself, emerge from its self-administration proceedings that have been ongoing since May 2023 and continue its solar integration business. Sono participated fully until the end of the project end 2025.

The revised situations of Atlas Technologies/Lightyear Layer and Sono Motors had an impact on the availability of vehicles that could be used for the monitoring campaign in Task 2. The consortium therefore prepared a mitigation plan to guarantee that a minimum number of vehicles were available for the monitoring campaign. This mitigation plan was incorporated in the inception report.

In August 2024, the project manager Dr. Wim Soppe from coordinator TNO left the project because of his retirement and his role was taken over by Dr. Jan Kroon.

Meetings

The daily progress of the project was reported in bi-weekly (later triweekly) meetings with DG-Move. Internally the consortium had meetings every four weeks in a videoconference.

Next to these online progress meetings, Physical meetings were held:

- April 19, 2023 in Düsseldorf on April 19
- June 16, 2023 in Munich
- October 11, 2023 in Eindhoven
- March 25, 2024 in Neuchâtel during the PV in Motion conference
- February 27, 2025 in Venray (Focus on Task 2)
- September 9,2025 in Düsseldorf. (Focus on Task 3)

Task 2 leader Fraunhofer ISE organized (bi-)weekly bilateral on-line meetings with TNO, IM Efficiency, Sono Motors and Lightyear Layer separately to discuss technical progress and planning, practical issues related to installed sensors.

Reporting:

The inception report was delivered according to schedule and approved in a meeting with DG-Move on March 30, 2023 in Brussels. The major comment and point of discussion were related to the topic of "smart charging" (V2G). It was agreed that smart charging algorithms would not be part of the modelling or assumptions in the project as smart charging algorithms and grid management add too much complexity. Instead, it was agreed that the assumption was made that any excess energy generated by the VIPV would be considered available for the grid.

The first interim report was delivered in Week 48 of the project (December 2023) and approved in a meeting with DG MOVE on 18 December 2023.

The second interim report was submitted at the end of April 2025. Project results were subsequently presented during an in-person meeting in Brussels on May 7, 2025. Following this, the consortium addressed comments and feedback from the European Commission, leading to the report's approval by DG MOVE via email on May 26, 2025

A preliminary version of the final report was submitted on December 1, 2026. Subsequently, during an online review meeting held on December 8, feedback was provided by DG MOVE. These comments were thoroughly addressed and incorporated, resulting in a revised and definitive version of the third report and the full report, which was then formally submitted on December 18, 2026. DG MOVE provided comments on the full report on December 19 and the final version of the full report was submitted and accepted by DG MOVE December 22.

Figure 113: In-person meeting with DG MOVE in Brussels, May 7, 2025

Figure 114: Face-to-face consortium meeting in Düsseldorf

4.2 Project progress and deviations

Task 1

The technical offer did not precisely define the number of archetypal vehicles that would be investigated in Task 1.1 (Potential and impacts of energy efficiency gains in electric vehicles). A number between 7 and 21 was assumed. In the Inception report the total number was set to 22. During the execution of Task 1, the involved partners noticed that the completion of all simulations for the 22 vehicle archetypes would require more time than scheduled. Consequently, the consortium asked permission to submit the first interim report in week 48 instead of week 40. DG MOVE accepted this under the condition that the planning of Task 2 would not be affected by this delay. Since the activities in Task 2 were largely independent of those in Task 1, the consortium agreed with this condition.

Task 2

Subtask 2.1 - Activity 2.1.1

The activities in Task 2.1.1 were carried out in the first reporting period and were described in the first interim report.

Subtask 2.1 - Activity 2.1.2

This activity started in December 2023 with the delivery and installation of the first irradiance sensors for IM Efficiency and SONO on their vehicle types to start the real-life measurements of solar irradiance as defined in the inception report under activity T2.1.2. The installation of sensors was continued by increasing the number of vehicles during the reporting period.

Lightyear got street approval for their PV powered Lightyear 0 from the Dutch RDW from September 2024 onwards. The irradiation sensor could not be positioned on the roof of the car as the car is fully covered with PV panels. Instead, an irradiance sensor was placed behind the front window with a tilt angle of 15° which did not affect the measurement campaign

According to the inception report, the measurement campaign was originally scheduled to conclude at week 120, following the submission of the second interim report. However, the consortium decided to extend the campaign through the end of the project, dedicating additional resources to broaden the driving range from Western and Central Europe to Southern Europe. Updates on the progress and outcomes of the measurement campaign, as contributed by ISE, Lightyear, IM Efficiency, and Sono Motors, are included in the final report.

Subtask 2.1 - Activity 2.1.3

According to the original plan, a final shortlist of vehicles and use cases for PV Integration testing as a starting point for the execution subtask 2.2 should have been defined at Month 60 (see also Milestone 2.3).

The partners search for suitable vehicles for the energy generation measurement campaign proved to be a difficult process and resulted in a significant delay compared to the indicative timeline as described in the inception report.

The final selection of vehicles for the energy measurement campaign is summarized below:

Table 60: Summary of the vehicle selection for the energy measurement campaign.

Partner	Available vehicle	Status
IM efficiency/TNO	PV powered E-Volvo	Raw energy data retrieved via a different project, only accessible to TNO and processed for model validation
Lightyear	Lightyear 0 (PV powered)	Operational since October 2024
Sono Motors	E-Van (non-PV) Vehicles with low voltage system available	Installation completed, but no street approval yet, test drive expected in April

Subtask 2.2

According to the inception report the measurement campaign should be completed at WK 120 after the submission of the second interim report, but it was decided to continue the measurement campaign until the end of the project to collect more data in Spring and Summer 2025 to further refine the modelling efforts and to support Task 3 activities.

In the second interim report we have reported on the selection of vehicles for the energy measurement campaign and were summarized below:

Table 61: Summary of the vehicle selection for the energy measurement campaign.

Partner	Available vehicle	Status
IM Efficiency/TNO	PV powered Volvo	Raw energy data retrieved via a different project, only accessible to TNO and processed for model validation
Lightyear	Lightyear 0 (PV powered)	Operational since October 2024
Sono Motors	E-Van (non-PV) Vehicle with low voltage system available	Energy consumption data retrieved by TNO via Sono for model validation

Subtask 2.2

According to the inception report the measurement campaign should have been completed at WK 120 after the submission of the second interim report, but based on the status mentioned above it was decided to continue the measurement campaign until the end of the project to collect more data in Spring and Summer 2025 to further refine the modelling efforts and to support Task 3 activities.

Subtask 2.3

The inception report describes a broad and general set of activities including comparison static PV with onboard PV, cost(model) &benefit, LCA, price for selling PV Power, attractiveness for users, qualitative criteria for benefits, risks and opportunities

The consortium decided to focus on one specific aspect namely the comparison of static PV with onboard PV as this topic has the best fit with the scope of Task 2. A selection of the other non-technical topics has been addressed in Task 3 (Chapter 3)

This subtask was considered as closed after the second interim report.

Task 3

Task 3 was carried out as scheduled, with all four subtasks progressing according to the original timeline and without significant deviations. The draft policy recommendation chapter was shared with DG MOVE at the end of October, 2025 and subsequently discussed during a meeting on November 4, 2025. Feedback and suggestions from this discussion were accepted and have been incorporated into the final report.

4.3 SolarMoves project planning

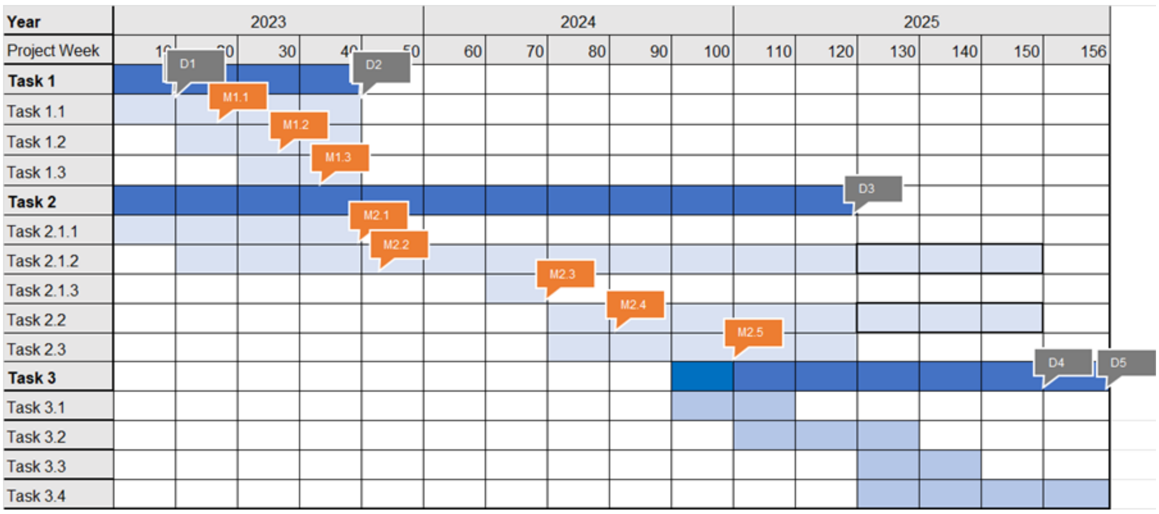


Figure 115: GANTT chart of the SolarMoves project planning

As outlined above, the GANTT chart illustrates that Tasks 2.1.2 and 2.2 were extended through Week 150, whereas Task 3 proceeded according to the original schedule without significant deviations. The consortium agreed to deliver the draft version of the final report (D4) by December 1, 2025, with the expectation that the final version will be submitted and approved before the Christmas break in 2025.

Table 62: List of Deliverables

No.	Date	Week	Description
D1	Mar 2023	10	Inception report
D2	Oct 2023	48	1st Interim report (task 1)
D3	apr-25	120	2nd interim report (task 2)
D4	nov-25	150*	Draft final report (task 3)
D5	dec-25	156	Final report

Table 63: List of Milestones

No	Week	Date	Description	Verification
M1.1	2	jan-23	Kick-off Meeting	Minutes agreed with Commission
M1.2	18	apr-23	Evolution of energy consumption reduction options for each vehicle class/use pattern	Graphical depiction of energy evolution for each vehicle class/use pattern
M1.3	26	jun-23	BEV potential per vehicle class	Visual communication prepared
M1.4	34	aug-23	Quantification of recharging infrastructure need	Presentation to Task Team
M2.1	40	Oct 2023	PV generation and demand for European-wide virtual routes calculated	Presentation to Task Team
M2.2	42	Oct 2023	Irradiance sensors installed on pilot vehicles	Photographs of installations
M2.3	60	March 2024	Short list of test vehicles identified	List approved by EAB
M2.4	70	apr-24	Nominal performance measurements completed for on-board PV systems	Visual communications of measurement results prepared
M2.5	75	May 2024	Test protocols for T2.2 defined and benchmarks identified	Approved by EAB
M3.1	140	aug-25	Likely future scenarios defined	Approved by EAB

Regarding the Milestones during the reporting period, the following explanations can be made:

Table 64: Explanation with respect to the Milestones

Milestone	Explanation/deviation
2.3	Achieved (see text under 2.1.3 in report), the milestone was achieved later than planned, not approved by EAB, but agreed by PB
2.4	Achieved, the vehicles with on-board PV have PV panels with a known STC performance
2.5	Partly achieved, Sono and Lightyear have developed some test protocols to simulate commuting, errands, and delivery system.

Table 65: Explanation with respect to the Milestones

Milestone	Explanation/deviation
3.1	Achieved (see Chapter 4), not approved by Executive Board (EAB), but agreed by Project Board

4.4 Dissemination

The following dissemination activities have been executed since the second interim report:

Table 66: Dissemination activities

Oral contributions	Written contributions
Anna Carr, Modelling the impact of VIPV, PV in Motion 2024, Neuchatel	Anna Carr et al., Solar Moves: Part 1, Modelling the impact of VIPV, Solar Energy Materials & Solar Cells 275 (2024) 113023
Anna Carr, SOLARMOVES: THE IMPACT ON GRID ELECTRICITY DEMAND OF VIPV at EUPVSEC 2024, Vienna	Public report SolarMoves: Modelling the impact of vehicle integrated photovoltaics on the electricity grid https://www.tno.nl/en/sustainable/energy-supply/solar-applications/solar-powered-cars/solar-potential-electric-vehicles/
Bart Kramer, Validation of energy usage and PV generation model for a passenger car, PVinMotion March 2025, Miyazaki, Japan	Anna J. Carr, Ashish Binani, Akshay Bhoraskar, Oscar van de Water, Michiel Zult, René van Gijlswijk, Lenneke Slooff-Hoek, *SolarMoves: The Impact on Grid Electricity Demand of VIPV,* EU PVSEC 2024, 020423-001 - 020423-004, ISBN: 3-936338-90-6, DOI: 10.4229/EUPVSEC2024/4DO.4.1
Anna Carr, Impact of shading model on the contribution of PV to the energy demand of a vehicle, PVinMotion March 2025, Miyazaki, Japan	Anna J. Carr , Lenneke H. Slooff, Ashish Binani, Christian Braun, Alexander Kleinhans, Ramakrishnan Kalyanasundaram, Ruud Derks , Jan M. Kroon, *Validation of shading model in SolarMoves*, Solar Energy Materials and Solar Cells 292 (2025) 113783
Alexander Kleinhans, Vehicle Archetype Weighted Solar Energy Potential on Vehicle Rooftops in Europe, PVinMotion March 2025, Miyazaki, Japan	Public report SolarMoves: Real life irradiance and energy consumption measurements for solar mobility.
Alexander Kleinhans, Solar Mobile Irradiance Measurements in Europe, PVinMotion March 2025, Miyazaki, Japan	Anna Carr, Antonius Burgers, Lenneke Slooff-Hoek, Jan Kroon, Christian Braun, Alexander Kleinhans, *VIPV shading model approach based on land use type*, Poster contribution, IPV conference, Florence, 25-26 November, Florence
Ruud Derks, Results of using solar panel systems on trailers, PVinMotion March 2025, Miyazaki, Japan	
Lenneke Slooff. Oscar vd Water, Outlook on the cost effectiveness of VIPV, PVinMotion March 2025, Miyazaki, Japan	
Ruud Derks, *VIPV: the experience of IM efficiency*, oral presentation, IPV conference, 25-26 November 2025, Florence	

Appendix A: Vehicle archetype characteristics

A1.1 Classification passenger cars (LP1x, LP2x, LP3x)

For the classification of small, medium and SUV passenger cars, we make an adjustment to the ACEA classification EU classification of vehicle types | European Alternative Fuels Observatory (europa.eu), which the European Commission follows. The adjustment is made, because it results in the best trade-off of representativeness and distinctiveness among the categories.

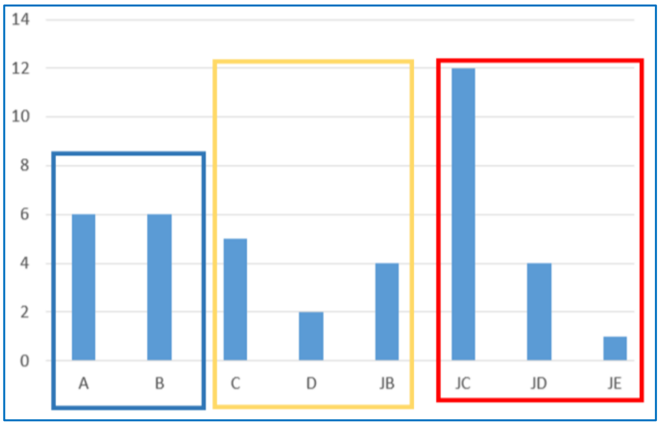


Figure 116: top 40 passenger EV sales and their division among the categories small (blue), medium (yellow) and SUV (red)

According to the ACEA classification SUV's (J) consist of small SUV's (JB), medium SUV's (JC and JD) and executive SUV's (JE). Figure 116 shows the top 40 most sold EV's, representing 93% of total passenger car EV sales in the EU (2020, 2021 and 2022), specified per ACEA defined segment. The coloured boxes indicate our defined categories: small (blue), medium (yellow) and red (SUV). We have added the small SUV's (JB) to the medium category, because it is more comparable in terms of characteristics to that category. Figure 117 shows the average frontal area of the different segments, which confirms that the small SUV's fit well in the medium category.

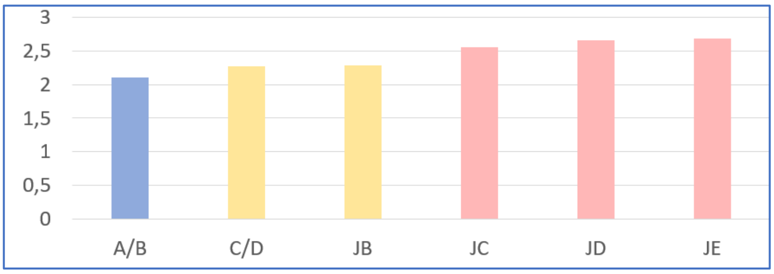


Figure 117: Frontal area (m^2) of the different categories compared

The resulting top 10's are shown in Table 67.

Table 67: top 10 most sold EV's per category

Small	Medium	SUV
RENAULT ZOE	TESLA MODEL 3	TESLA MODEL Y
FIAT 500E	VW ID.3	VW ID.4
PEUGEOT E-208	HYUNDAI KONA	SKODA ENYAQ
DACIA SPRING	NISSAN LEAF	KIA E-NIRO
VW E-UP!	PEUGEOT E-2008	AUDI E-TRON QUATTRO
SMART FORTWO	POLESTAR 2	AUDI Q4 E-TRON
MINI COOPER SE	OPEL/VXH. MOKKA-E	HYUNDAI IONIQ 5
RENAULT TWINGO	RENAULT MEGANE	VOLVO XC40
OPEL/VXH. CORSA-E	CUPRA EL-BORN	FORD MUSTANG MACH-E GT
BMW I3	VW E-GOLF	MERCEDES EQA

A1.2 Classification of vans (LV1x, LV2x)

For the vans, we have defined two categories: small vans and large vans. The two categories are distinguished by mass. In Directive 2007/46/EC, vans (N1) consist of three mass categories (I, II and III). We set the mass cut-off point for small vans and large vans at half of the empty mass of category II. The group of large vans (LV2x) is extended to a gross vehicle weight (GVW) of 4,250 kg, due to a proposal currently being considered by the EP to allow electric vans up to that GVW to be driven by people with driver's licence B (i.e. beyond the normal 3,500 kg).

A1.3 Classification of busses (HB1x, HB2x)

The busses are classified into two categories: the low-floor busses (HB1x) and high-floor coaches (HB2x). These categories are distinguished based on their function. The low-floor busses have the city busses and the regional busses that are used as public transportation. The high-floor coaches have the regional coaches and the long-distance travel.

A1.4 Classification of trucks/tractors (HT1x, HT2x)

The heavy duty trucks and tractor-trailers are also split into two categories each. The rigid trucks operate in urban and regional conditions while the tractor-trailers operate in a regional and long-haul freight transport.

A2 Data

For each vehicle archetype, the top 5 or 10 sales in Europe (Netherlands for heavy-duty vehicles) was taken from [56] and [57].

[56] European Alternative Fuels Observatory (EAFO), https://alternative-fuels-observatory.ec.europa.eu; detailed data from personal exchange with FIER Automotive

[57] Dutch type approval database, https://opendata.rdw.nl

A2.1 Small passenger cars

	Gross battery size	Usable battery size		Lower charging limit	AC charging losses	AC (max) charging power	Energy Consumption	DC charging losses	DC charging power
	kWh	kWh		%	%	kW	Wh/km	%	kW
RENAULT ZOE BEV	54.7	52		100		22	165		46
FIAT 500E BEV (42kWh)	42	37.3		100		11	159		85
PEUGEOT E-208 BEV	50	46.3		100		11	160		101
DACIA SPRING BEV	27.4	25		100		6.6	152		34
VW E-UP! BEV	36.8	32.3		100		7.2	158		40
SMART FORTWO BEV	17.6	16.7		100		7	167		-
MINI COOPER SE BEV	32.6	28.9		100		11	161		49
RENAULT TWINGO BEV	23	21.3		100		22	164		-
OPEL/VXH. CORSA-E BEV	50	46.3		100		11	157		101
BMW I3 BEV	42.2	37.9		100		11			50
									49.5
Average	37.6	34.4		100	15	12.0	160	10	63.3
Min	17.6	16.7		100	0	6.6	152	0	34
Max	54.7	52		100	0	22	167	0	101

A2.2 Medium size passenger cars

	Gross battery size	Usable battery size	Crr of tyres	Upper charging limit	Lower charging limit	AC charging losses	AC charging power level	Energy Consumption	DC charging losses	DC charging power level
	kWh	kWh	-	%	%	%	kW	Wh/km	%	kW
TESLA MODEL 3	82	76		0	100		11	151		250
VW ID.3 BEV	62	58		0	100		7.2	166		118
HYUNDAI KONA BEV	42	39.2		0	100		11	157		77
NISSAN LEAF BEV	62	59		0	100		6.6	166		100
PEUGEOT E-2008 BEV	50	46.3		0	100		11	178		101
POLESTAR 2 BEV	78	75		0	100		11	174		151
OPEL/VXH. MOKKA-E BEV	50	46.3		0	100		11	178		101

RENAULT MEGANE BEV	65	60		0	100		22	167		130
CUPRA EL-BORN BEV	62	58		0	100		11	166		124
VW E-GOLF BEV	35.8	32		0	100		7.2	168		44
										110
Average	58.9	55.0		0	100	0.15	10.9	167.1	0.1	129
Min	42	39.2	0	0	100	0	6.6	151	0	77
Max	82	76	0	0	100	0	22	178	0	250

A2.3 SUV

	Gross battery size	Usable battery size	Crr of tyres	Upper charging limit	Lower charging limit	AC charging losses	AC charging power level	Energy Consumption	DC charging losses	DC charging power level
	kWh	kWh	-	%	%	%	kW	Wh/km	%	kW
TESLA MODEL Y	78.1	75		0	100		11	167		250
VW ID.4 BEV	82	77		0	100		11	188		118
SKODA ENYAQ BEV	62	58		0	100		11	178		135
KIA E-NIRO BEV	67.5	64		0	100		11	171		100
AUDI E-TRON QUATTRO BEV	95	86.5		0	100		11	202		155
AUDI Q4 E-TRON BEV	82	76.6		0	100		11	189		135
HYUNDAI IONIQ 5 BEV (stand. range)	73	70		0	100		11	183		233
VOLVO XC40 BEV	78	75		0	100		11	191		151
FORD MUSTANG MACH-E GT BEV	75.7	70		0	100		11	214		107
MERCEDES EQA BEV	69.7	66.5		0	100		11	187		112
										135
Average	76.3	71.9		0	100	0.15	11	187	0.1	150
Min	62	58	0	0	100	0	7.2	167	0	50
Max	95	86.5	0	0	100	0	11	216	0	250

A2.4 Small Van

	Gross battery size	Usable battery size	Crr of tyres	Upper charging limit	Lower charging limit	AC charging losses	AC charging power level	Energy Consumption	DC charging losses	DC charging power level
	kWh	kWh	-	%	%	%	kW	Wh/km	%	kW
Renault Kangoo BEV	44	39.6					11			80
Streetscooter Work BEV	40	36								
Nissan E-NV200 BEV	40	36					6.6			50
Peugeot E-Partner BEV	50	45					11			100
Citroen E-Berlingo VAN BEV	50	45					11			100
VW E-CADDY BEV	38.8	34.9					7.2			50
OPEL COMBO-E L1H1	50	45					11			100
Average (top5)	45.5	40.92					11			100

A2.5 Large van

	Gross battery size	Usable battery size	Crr of tyres	Upper charging limit	Lower charging limit	AC charging losses	AC charging power level	Energy Consumption	DC charging losses	DC charging power level
	kWh	kWh	-	%	%	%	kW	Wh/km	%	kW
MERCEDES EVITO VAN BEV	100	90					11			110
MERCEDES ESPRINTER VAN BEV	47	42.3					7.4			80
PEUGEOT E-EXPERT BEV	75	68					11			100
CITROEN E-JUMPY BEV	75	68					11			100
TOYOTA PROACE VAN BEV	75	68					11			100
OPEL/VXH. VIVARO-E BEV (L2H1)	75	68					11			100
Average (top5)	74.5	67.4					11			100

A2.6 Low-floor bus

		Gross battery size	Usable battery size	Crr of tyres	Upper charging limit	Lower charging limit	AC charging losses	AC charging power level	Energy Consumption	DC charging losses	DC charging power level
		kWh	kWh	-	%	%	%	kW	Wh/km	%	kW
BYD	BYD EBUS	422	380								
VDL	CITEA SLF-120/ELECTRIC	288	259								430
EBUSCO	2.2	350	315								
VDL	CITEA SLFA-180/ELECTRIC	420	378								330
VDL	CITEA SLFA-181/ELECTRIC	420	378								330
VDL	CITEA LLE-99/ELECTRIC	216	194								245
HEULIEZ BUS	GX 437 ELEC	250	225								450
VDL	CITEA LLE-115/ELECTRIC	216	194								245
Average top 8		323	290								
Average top 3 (12m buses)		353	318								
Average top 5		380	342								
Average 18m buses		363	327								

A2.7 High-floor coach

For the high-floor coach, the properties were set equal to those of the low-floor bus, due to a lack of data.

A2.8 Rigid truck

		Gross battery size	Usable battery size	Crr of tyres
Urban distribution		kWh	kWh	-
DAF	LF Electric	282	253.8	
Volvo	FL electric	282	253.8	
Renault	D Z.E	280	252	
Mercedes	eActros 300	336	302.4	
Average		295	265.5	0.006

Regional distribution				
DAF	LF Electric	216	194	
Volvo	FL electric	250	225	
Renault	D Z.E	216	194	
Mercedes	eActros 300	323	290	
Average		353	318	0.006

A2.9 Tractor-trailer

		Gross battery size	Usable battery size	Crr of tyres
Regional distribution and long haul		kWh	kWh	-
Volvo	FM Electric	540	486	
Volvo	FH electric	540	486	
Mercedes	eActros	336	302.4	
DAF	CF Electric	350	315	
Average		441.5	397.35	0.006

Appendix B: Trip definitions

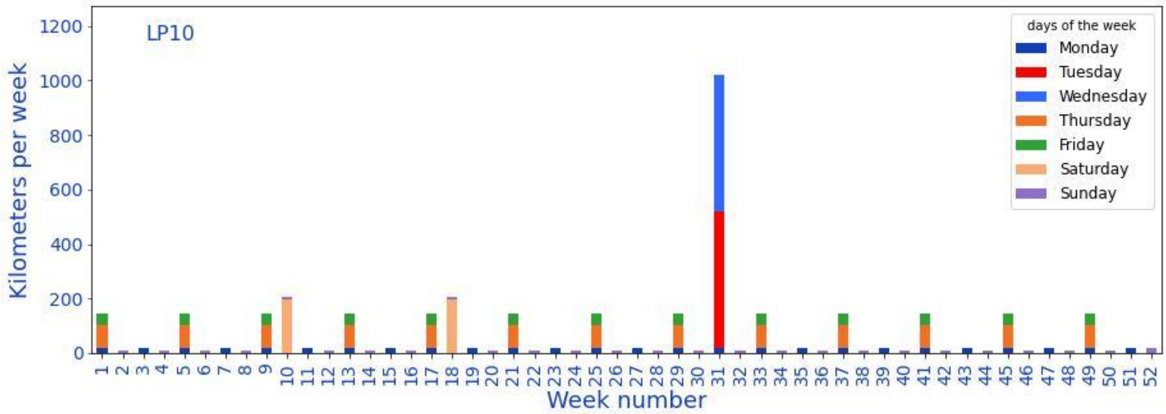
B1 Small Passenger cars

Table 68: Description of passenger vehicle archetypes, including annual mileage and distribution over road types

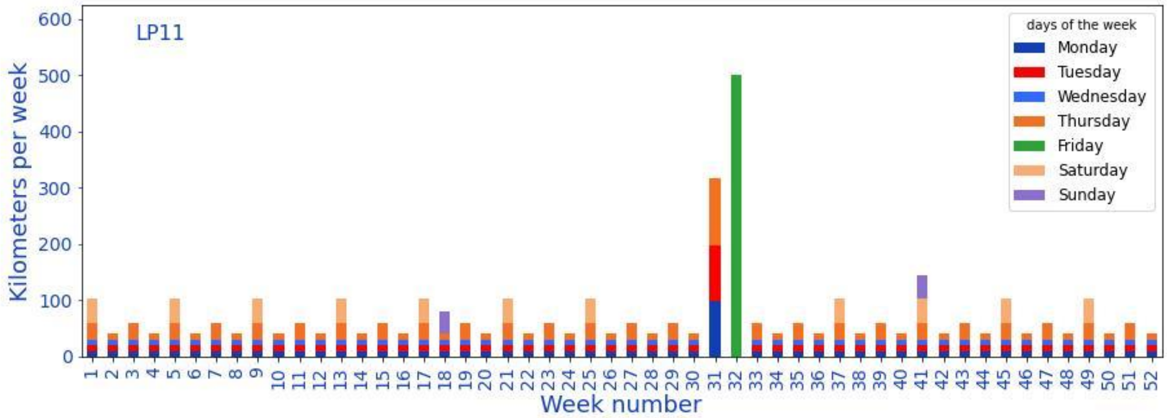
Vehicle type	Vehicle class and type	Use pattern	Description	Annual mileage (km)	Urban	Rural	Motorway
LP10	Small passenger car	Occasional use	Cars that are driven a few times a week	3795	21%	42%	37%
LP11	Small passenger car	Daily urban commute	Cars that are driven mostly in urban areas on a daily basis	3894	70%	10%	20%
LP12	Small passenger car	Daily peri urban commute	Cars of people that live outside the city and/or use their car on a daily basis to commute to rural areas	8099	20%	70%	10%
LP13	Small passenger car	Long-distance highway travel	Cars that commute most of their mileage on motorways for long-distance travel, due to business and holidays	14479	10%	20%	70%
LP14	Small passenger car	Car sharing		16237	26%	33%	42%

Table 69: trip definitions for passenger cars per vehicle archetype

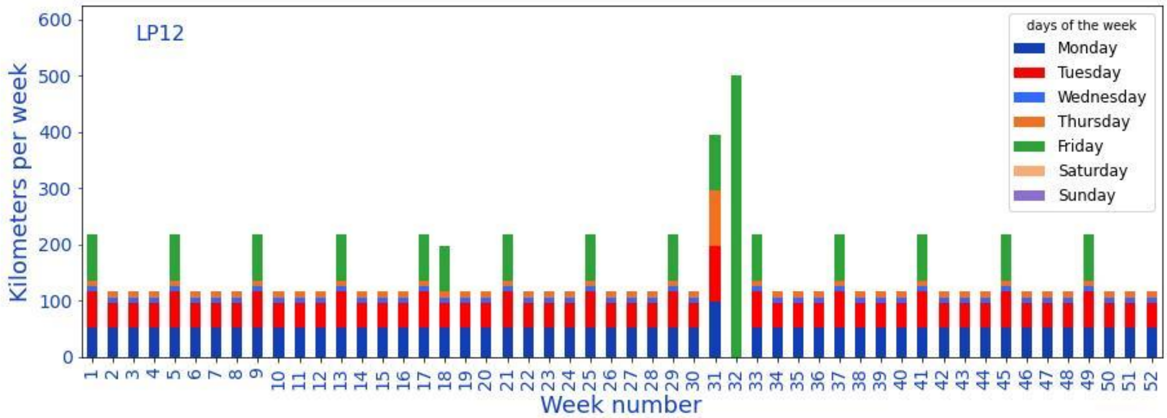
	LP10			LP11			LP12			LP13			LP14		
Trip Type	Days	Time	Total in the year	Days	Time	Total in the year	Days	Time	Total in the year	Days	Time	Total in the year	Days	Time	Total in the year
5 km	Mondays	11:00	52	Mondays – Thursdays (excl. holidays)	09:00, 17:00	400	Mondays – Fridays (excl. holidays)	20:00	250	Mondays – Fridays (excl. holidays)	09:00, 17:00	250	Monday-Friday (excl. 2 week summer)	12:00 13:00	250 50
10 km	Mondays	12:00	52	Thursdays	20:00	52	Thursdays	20:00	32	Thursdays (January – June + September – November)	20:00	32	Monday-Friday (excl. 2 week summer)	14:00	250
20 km	Every other Thursday	14:00	26	1st Saturday of month + 2 random Saturdays	10:00	14	Mondays, Wednesdays Tuesdays, Thursdays	09:00 17:00	100 100	Every Saturday	10:00, 16:00	100	Tuesdays, Wednesdays, Fridays (excl. 2 week summer)	09:00	150
40 km	Every other Thursday	16:00	26	2 random Sundays	10:00	2	Every other Friday	09:00	27	1st Saturday of month + 3 random Saturdays	12:00	15	Wednesday	17:00	52
100 km	1 trip every Tuesday in February, June, September, November	10:00	4	3 trips in August week 1	any	3	4 trips in August week 1	any	4	Every Sunday	10:00	52	Sundays	10:00	52
500 km	2 trips in August week 1	09:00	2	1 trip in August week 1	any	1	1 trip in August week 1	any	1	1 trip in August every week	any	4			
1000 km	-	-	-	-	-	-	-	-	-	2 days in July and 1 in December	any	3			



LP10
Kilometers per week
Week number
days of the week
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday



LP11
Kilometers per week
Week number
days of the week
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday



LP12
Kilometers per week
Week number
days of the week
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday

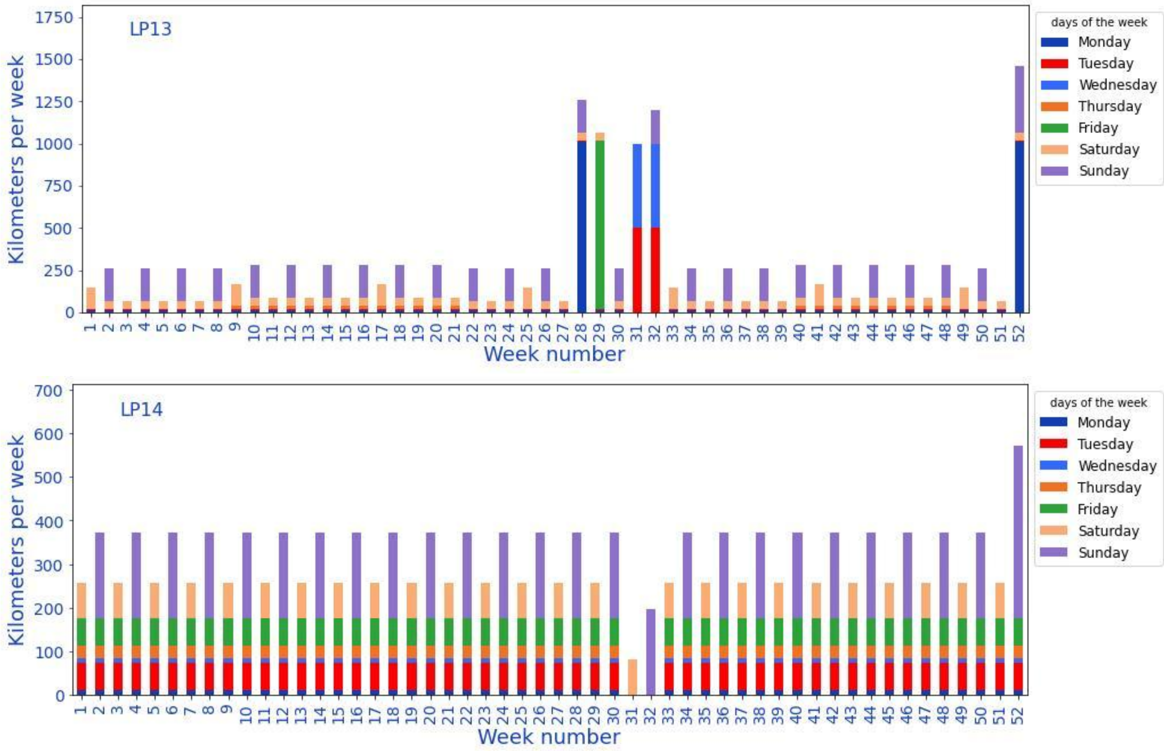


Figure 118: Weekly kilometre profile charts for each archetype: LP10 – LP14

B2 Medium Passenger cars

For the small passenger car archetypes this approach results in the following annual travel distance and division over the different road types. See Table 70 and Table 71.

Table 70: Description of medium passenger vehicle archetypes, including annual mileage and distribution over road types

Vehicle type	Definition	Description	*Annual mileage (km)*	Urban	Rural	Motor way
LP21	Medium Passenger car, daily urban distribution	"Cars that are driven mostly in urban areas on a daily basis".	5164	70%	10%	20%
LP22	Medium Passenger car, daily peri urban distribution	"Cars of people that live outside of the city and or use their car on a daily basis to commute to rural areas".	10548	20%	70%	10%
LP23	Medium Passenger car, long-distance highway travel	"Cars of people that live outside of the city and or use their car on a daily basis to commute to rural areas".	20619	20%	10%	70%

Table 71: trip definitions for medium passenger cars per vehicle archetype

	LP21			LP22			LP23		
Trip Type	Days	Time	Total in the year	Days	Time	Total in the year	Days	Time	Total in the year
5 km	Mondays – Fridays (excl. holidays) Mondays, Wednesdays (excl. holidays)	19:00 21:00	250 100	Mondays – Fridays (excl. holidays) Wednesdays (excl. holidays)	19:00 21:00	250 50	Mondays – Fridays (excl. holidays) Wednesdays (excl. holidays)	19:00 21:00	250 50
10 km	Thursdays (not in July, August and 2 weeks in December)	20:00	42	Thursdays (not in July, August and December)	20:00	40	Thursdays (not in July, August and December)	20:00	40
20 km	Saturday (February-April + October-November)	10:00	20	Mondays, Tuesday, Wednesday (excl. holidays) Wednesdays, Thursdays, Fridays (excl. holidays)	09:00 17:00	150 150	Mondays, Tuesday, Wednesday (excl. holidays)	09:00	150
40 km	3 random Sundays	10:00	3	Mondays (not in July, August, December, January)	17:00	36	Tuesdays (in March, April, May, October, November)	20:00	20
100 km	5 trips in August week 1 and 2	any	5	4 trips in August week 1	any	4	Sundays Sundays (once every three weeks)	10:00 18:00	52 18
500 km	1 trip in August week 2, Saturday	any	1	1 trip in August week 2,Friday	any	1	1 trip every week in August + 2 trips in December	any	6
1000 km				2 trips in July and 2 in December	any	4	2 trips in July and 2 in December	any	4

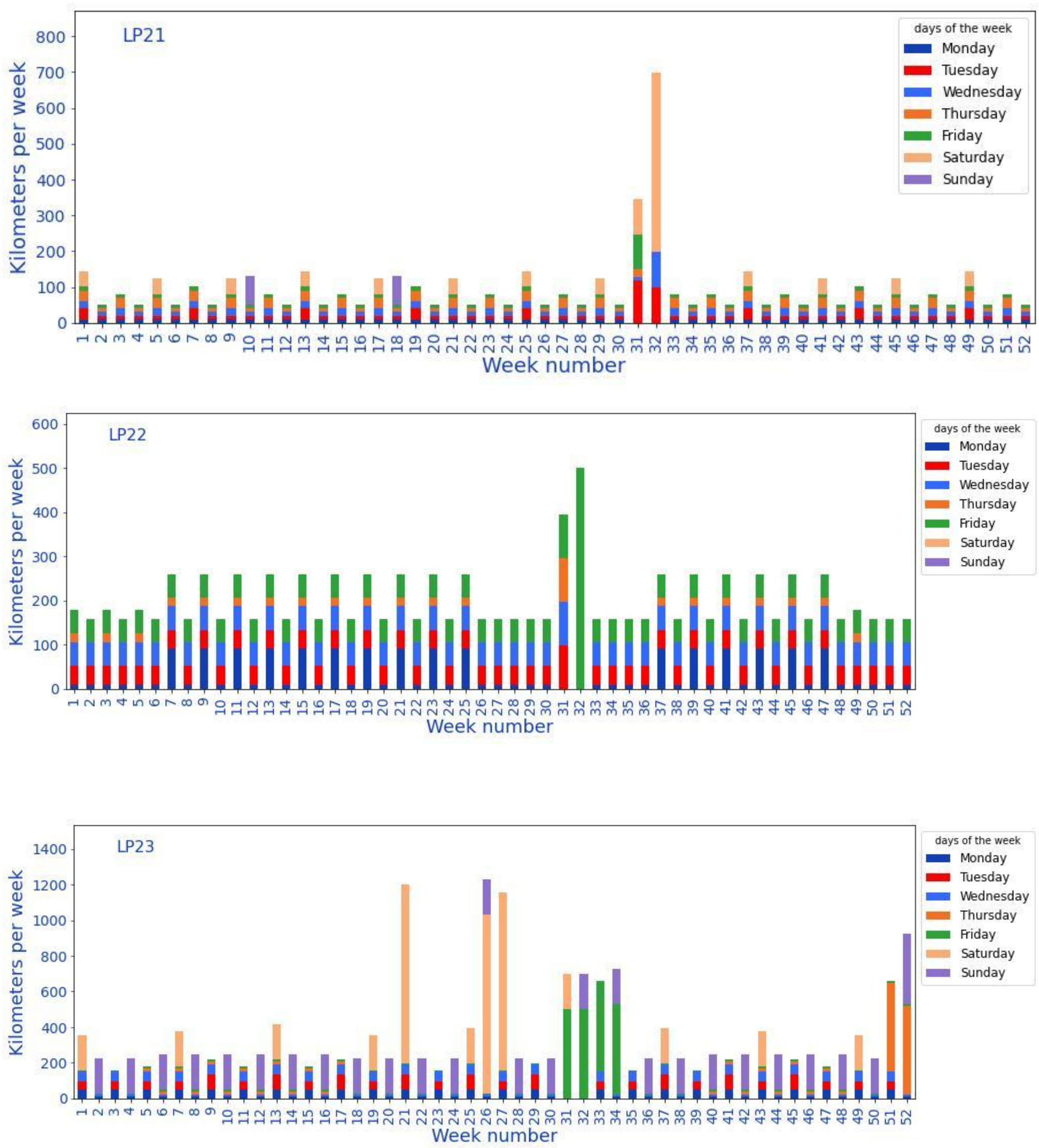


Figure 119: Annual driving profiles of some passenger cars, showing total weekly kilometres by day

B3 SUV

For the small passenger car archetypes this approach results in the following annual travel distance and division over the different road types. See Table 72 and Table 73.

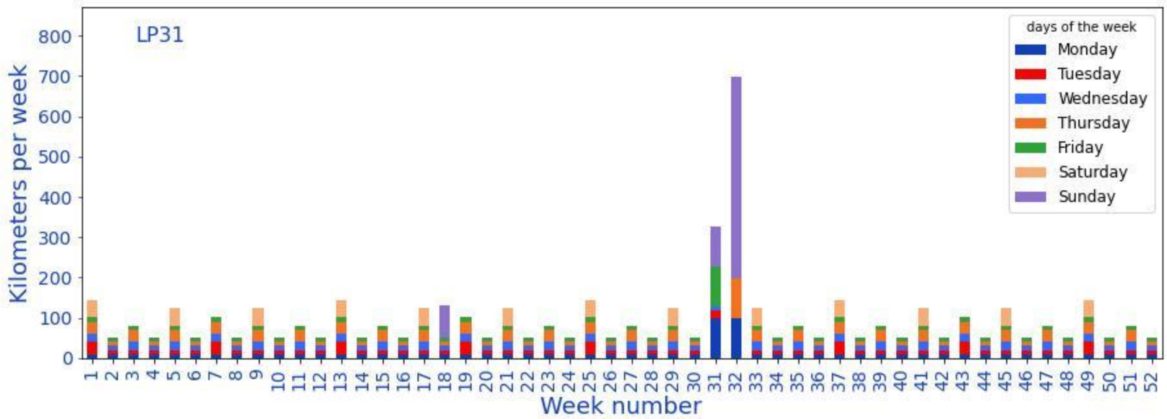
Table 72: Description of SUV vehicle archetypes, including annual mileage and distribution over road types

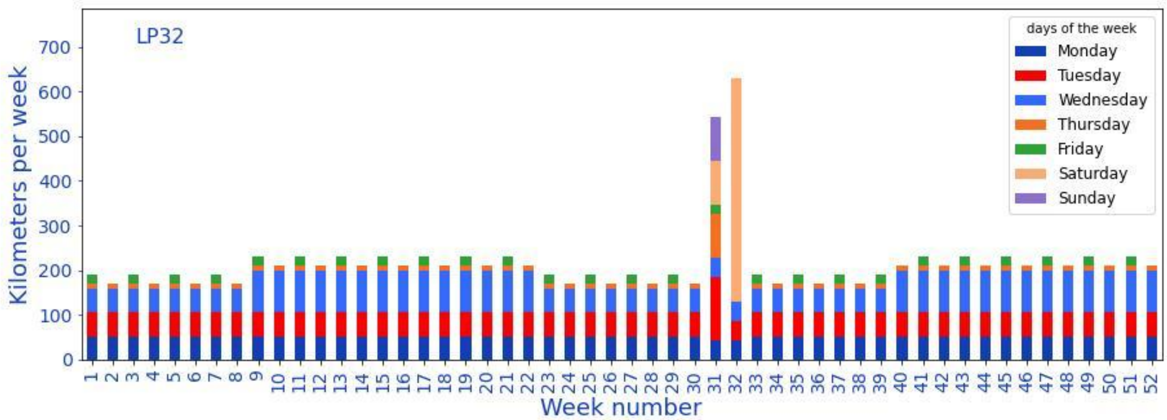
Vehicle type	Definition	Description	*Annual mileage (km)*	Urban	Rural	Motor way
LP31	SUV daily urban distribution	"Cars that are driven mostly in urban areas on a daily basis".	5016	70%	10%	20%
LP32	SUV daily peri urban distribution	"Cars of people that live outside of the city and or use their car on a daily basis to commute to rural areas".	11230	20%	70%	10%
LP33	SUV long-distance highway travel	"Cars that commute most of their mileages on motorways for long-distance travel, due to business and holidays".	20619	20%	10%	70%

Table 73: trip definitions for SUV's per vehicle archetype

	LP31			LP32			LP33		
Trip Type	Days	Time	Total in the year	Days	Time	Total in the year	Days	Time	Total in the year
5 km	Mondays – Fridays (excl. holidays) Wednesdays	09:00; 17:00 18:00	500 52	Mondays – Fridays (excl. holidays) Wednesdays - Saturdays (excl. holidays)	19:00 21:00	250 200	Mondays – Fridays (excl. holidays) Wednesdays (excl. holidays)	19:00 21:00	250 50
10 km	Thursdays Tuesdays once in three weeks	20:00 20:00	40 18	Thursdays (not in August and 2 weeks in December)	20:00	46	Thursdays (not in July, August and December)	20:00	40
20 km	Saturday (February-April + October-November)	10:00	22	Mondays, Tuesday, Wednesday (excl. holidays) Tuesdays, Wednesdays, Thursdays, Fridays (excl. holidays)	09:00 17:00	156 208	Mondays, Tuesday, Wednesday (excl. holidays)	09:00	150

40 km	3 random Sundays	10:00	3	Mondays (not in July, August, December)	17:00	40	Tuesdays (in March, April, May, October, November)	20:00	20
100 km	5 trips in August week 1 and 2	any	5	4 trips in August week 1	any	4	Sundays Sundays (once every three weeks)	10:00 18:00	52 19
500 km	1 trip in August week 3	any	1	1 trip in August week 2	any	1	1 trip every week in August + December	any	8
1000 km							2 trips in July and 2 in December week 4	any	4





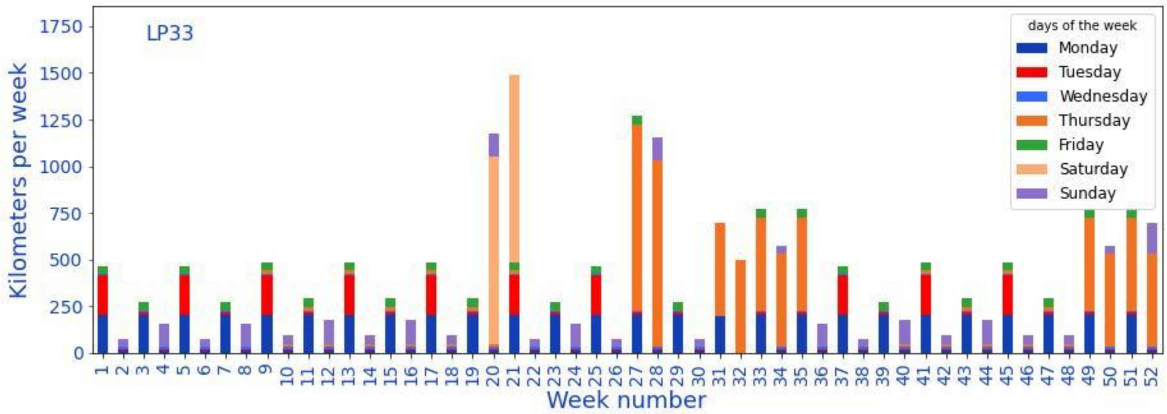


Figure 120: Weekly kilometre profile charts for each archetype: LP31 – LP33

B4 Vans

For the vans archetypes this approach results in the following annual travel distance and division over the different road types. See Table 74 and

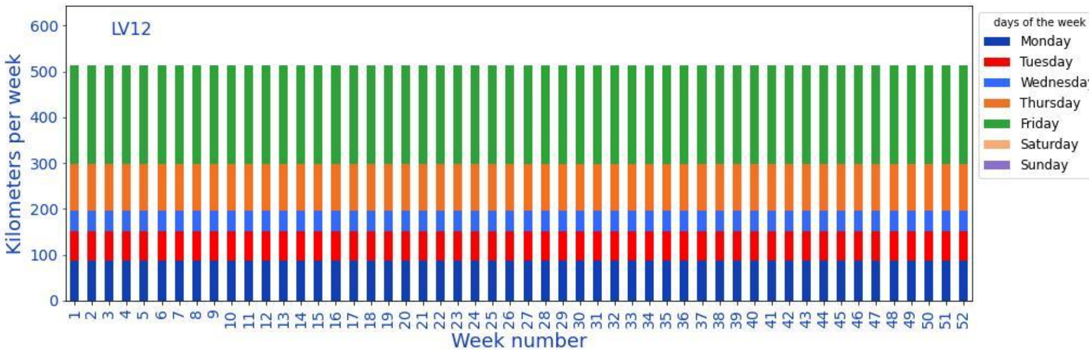
Table 75.

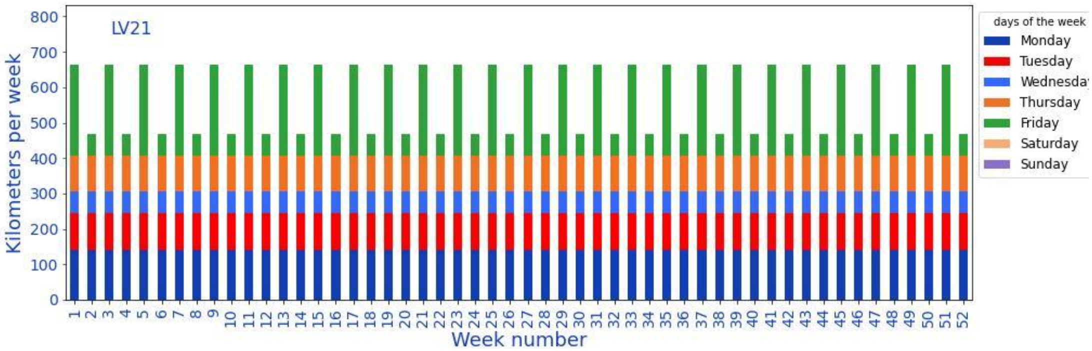
Table 74: Description of van vehicle archetypes, including annual mileage and distribution over road types

Vehicle type	Definition	*Annual mileage (km)*	Urban	Rural	Motor way
LV11	Small van, local distribution	19059	40%	20%	30%
LV12	Small van, regional distribution	26752	20%	40%	30%
LV21	Large van, local distribution	29464	40%	20%	30%
LV22	Large van, regional distribution	23519	20%	40%	30%

Table 75: trip definitions for vans per vehicle archetype

	LV11			LV12			LV21			LV22		
Trip Type	Days	Time	Total in the year	Days	Time	Total in the year	Days	Time	Total in the year	Days	Time	Total in the year
5 km	Mon– Thur excl. holidays Fri excl. holidays	9AM 10AM 11AM 3PM 4PM 10AM 11AM 3PM 4PM	1040 260	Mondays – Wednesdays (excl. holidays) Thursdays, Fridays (excl. holidays)	9:00, 10:00, 11:00 10:00, 11:00	468 208	Mondays (excl. holidays) Tuesdays-Fridays (excl. holidays)	09:00, 10:00, 11:00, 12:00, 14:00, 15:00, 16:00 09:00, 10:00, 11:00, 14:00, 15:00, 16:00	364 1248	Mondays – Fridays (excl. holidays)	9:00, 10:00, 11:00	750
10 km	Mon, Tue, Fri	12:00	156	Mondays, Fridays (excl. holidays)	12:00	100	Tuesdays-Fridays (excl. holidays))	12:00	200	Tuesdays - Fridays (excl. holidays)	12:00	200
20 km	Mondays, Fridays (excl. holidays))	13:00	100	Mondays-Thursdays (excl. holidays) Every other Friday (excl. holidays)	13:00 13:00	200 25	Mondays, Wednesdays (excl. holidays) Every other Saturday (excl. holidays)	13:00 13:00	100 25	Mondays-Fridays (excl. holidays)	13:00	250
40 km	Tuesdays (excl. holidays and January)	20:00	46	Tuesdays (excl. holidays) Every other Friday (excl. holidays)	14:00, 16:00 14:00	100 25	Tuesdays (excl. holidays) First Friday of the month	20:00 20:00	50 12	Mondays, Wednesdays, Saturdays (excl. holidays)	19:00	150
100 km	Friday	08:00	52	Fridays Every first Friday of the month	08:00 17:00	52 12	Friday (excl. holidays) Frist Thursday and Friday of the month	08:00 18:00	50 24	Fridays Every first Friday of the month	08:00 17:00	52 12





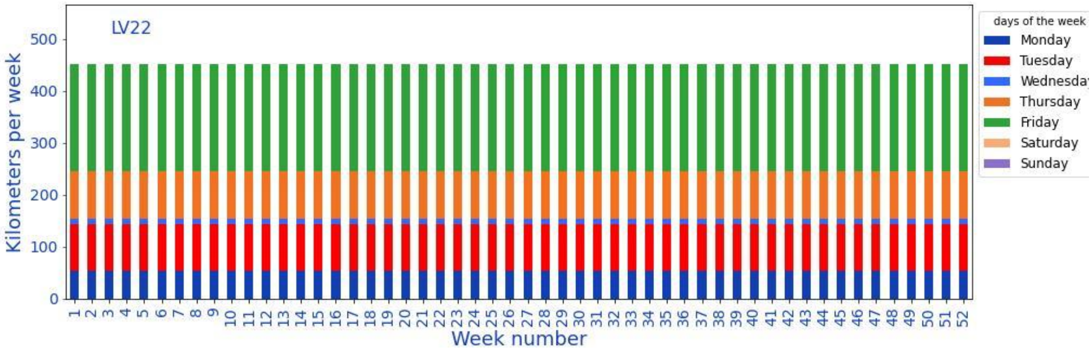


Figure 121: Weekly kilometre profile charts for each archetype: LV12, LV13, LV21 & LV22

B5 Trucks

The use pattern annual distribution of a truck is more predictable. It is assumed that they have 260 working days (52 weeks of 5 days). There are three types of working days for each truck archetype:

Type 1: Three days of the week is with the average daily mileage (Tuesday, Wednesday, Thursday)
Type 2: One day is with the average daily mileage plus the standard deviation (Monday)
Type 3: One day is with the average daily mileage minus the standard deviation (Friday)

Each archetype has a different distribution of trips. They all consist of a combination of a 10 km urban trip, 40 km rural trip and a 100 km motorway trip. The distribution is chosen such that the annual mileage and the distribution of urban, rural and motorway are met.

Table 76: Description of truck vehicle archetypes, including annual mileage and distribution over road types

Vehicle type	Definition	*Annual mileage (km)*	Urban	Rural	Motor way
HT11	urban distribution	46523	66%	15%	19%
HT12 & HT22	Tractor and Rigid – regional distribution	80166	43%	31%	26%
HT13	Tractor – long-haul freight transport	141336	26%	24%	50%

Table 77: trip definitions for trucks per vehicle archetype.

	THT11			**HT12 & HT22**			**HT23**		
Start time	Trip type 1	Trip type 2	Trip type 3	Trip type 1	Trip type 2	Trip type 3	Trip type 1	Trip type 2	Trip type 3
05h00				100 km motorway			100 km motorway	100 km motorway	100 km motorway
06h00					100 km motorway	40 km rural			
07h00	100 km motorway	100 km motorway	40 km rural	100 km motorway			100 km motorway	100 km motorway	40 km rural
08h00						40 km rural			
09h00			10 km urban		40 km rural		10 km urban	10 km urban	40 km rural
10h00	10 km urban	10 km urban	10 km urban	40 km rural		10 km urban	100 km motorway	100 km motorway	
11h00	10 km urban	10 km urban	10 km urban		10 km urban	10 km urban			10 km urban
12h00				10 km urban	40 km rural	10 km urban	100 km motorway	100 km motorway	10 km urban
13h00	10 km urban	10 km urban	10 km urban	10 km urban		10 km urban			40 km rural
14h00	100 km motorway	10 km urban	10 km urban	40 km rural	10 km urban	10 km urban	100 km motorway	100 km motorway	
15h00		40 km rural	40 km rural		10 km urban	10 km urban			40 km rural
16h00				100 km motorway	100 km motorway	40 km rural	40 km rural	40 km rural	
17h00									40 km rural
18h00						40 km rural	40 km rural	10 km urban	
19h00								10 km urban	100 km motorway
20h00							40 km rural		

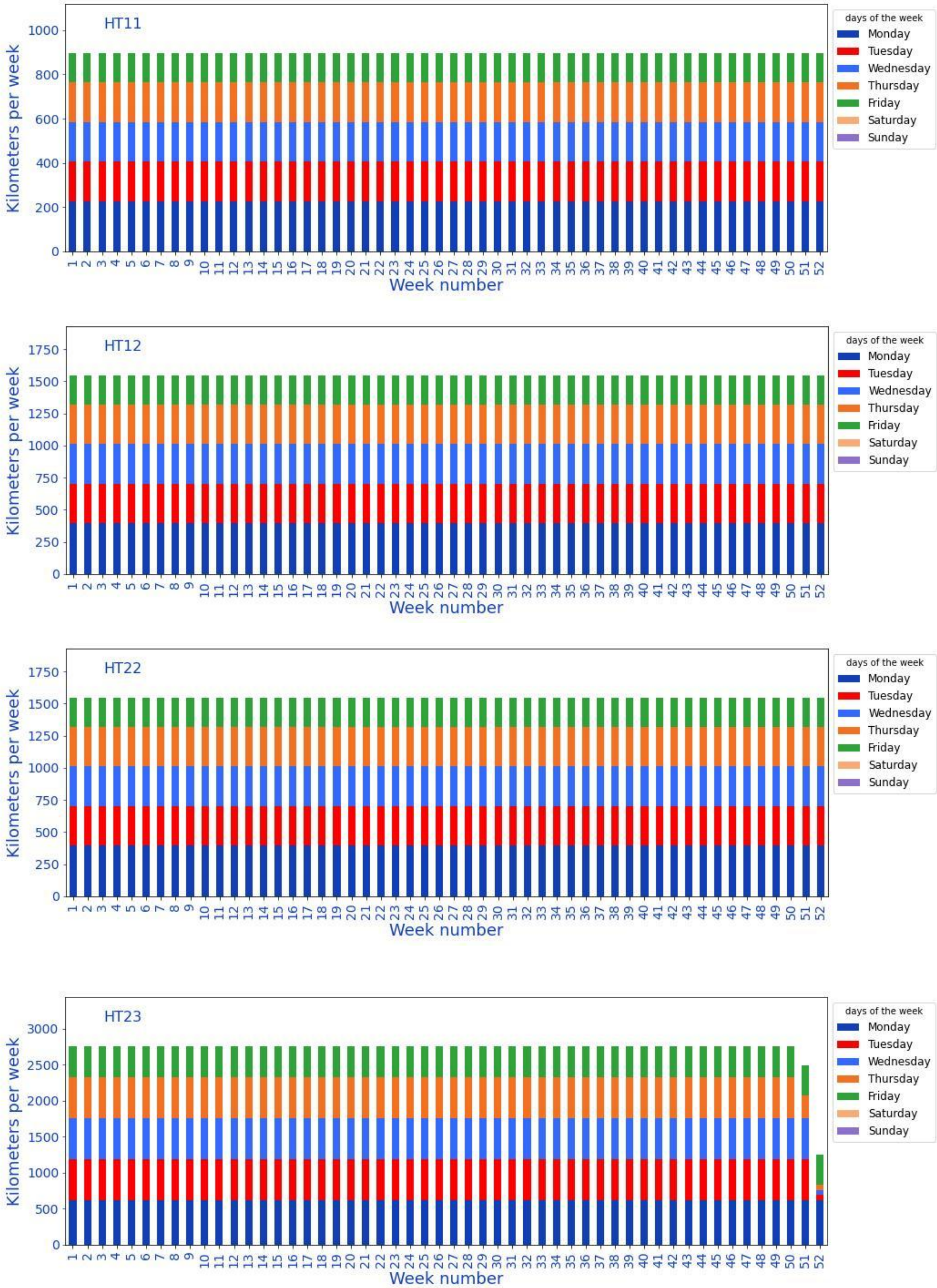


Figure 122: Weekly kilometre profile charts for each archetype: HT11, HT12, HT22, HT23

B6 Buses

Table 78: Description of bus vehicle archetypes, including annual mileage and distribution over road types

Vehicle type	Definition	*Annual mileage (km)*	Urban	Rural	Motor way
HB11	Low-floor bus, Urban public transport service	100296	80%	20%	0%
HB12	Low-floor bus, Peri urban public transport service	66170	50%	44%	6%
HB22	High-floor coach, Regional public transport	63872	9%	34%	57%
HB23	High-floor coach, Long Distance Highway travel	90273	4%	9%	87%

HB11 – Low-floor bus, Urban public transport service

Low-floor buses in urban transport service follow a pattern derived from monitoring data in Amsterdam for the Dutch heavy-duty in-service emissions monitoring program[58]. A week of service was taken, and modified to allow for charging.

HB12 – Low-floor bus, Peri urban public transport service

The same approach was followed as for HB11, except that data for a rural bus service in the area of ‘s Hertogenbosch was taken from the same study.

HB22 – High-floor coach, Regional public transport

High-floor bus uses the same line/trip every day throughout the year.

Table 79: trip definitions for low-floor buses, regional public transport service

Start time	Trip type
08h00	5 km urban
09h00	20 km rural
10h00	100 km motorway
13h00	40 km rural
14h00	10 km urban

HB23 – High-floor coach, Long Distance Highway travel

High-floor bus uses the same line/trip every day throughout the year for three times per week (on Tuesdays, Thursdays and Saturdays).

[58] Vermeulen, R., Gijlswijk, R. van and Goethem, S. van, Tail-pipe NOx emissions of Euro VI buses in daily operation in the Netherlands, TNO 2018 R11328, November 2018.

Table 80: trip definitions for high-floor coaches, long distance highway travel

Start time	Trip type
06h00	10 km urban
07h00	20 km rural
08h00	20 km rural
09h00	10 km urban
10h00	500 km motorway
17h00	20 km rural
18h00	10 km urban

Figure 123: Weekly kilometre profile charts for each archetype: HB11, HB12, HB22, HB23

Appendix C: Energy consumption of auxiliary systems

Auxiliary systems other than air conditioning and heating

The auxiliary energy consumption of vehicles, excluding air conditioning and heating, was derived from literature and analysis of measurement data.

For passenger cars, measurement data was used, partially from the H2020 project "Green Vehicle Index" (https://cordis.europa.eu/project/id/814794). For five electric vehicles test data was selected where v<0.5, i.e. stationary, and with the vehicle in active state, e.g. at a traffic light. For each vehicle, the 10-percentile of the battery discharge power was calculated, as a measure for the energy consumption without (significant) air conditioning or heater consumption. The average value was 900W.

For trucks, the value was taken from the TNO Advance model: 4000W.

For buses the auxiliary systems are assumed to consume 5000W on average: 1 kW for the air system, 2 kW of load on the 24V system and 2.5kW for the power steering. Data is taken from a confidential TNO report of 2016.

Airconditioning and heating

The heating and cooling power needed were determined using the following formulas. The formulas for passenger cars were based on an analysis of the work described in a paper by Evtimov[59]. For buses the formulas were derived from an analysis of the HVAC energy consumption reduction potential in a confidential TNO report of 2016, combined with a calculation of internal heat load (100W per person) and an assumption of the coefficient of performance of the installation of 2.5 and 3.5 for cooling and heating, which is assumed to deteriorate by 0.1 for every 5 degrees temperature difference.

The desired cabin temperature (T_{inside}) was assumed to be 21°C and it was assumed that heating works only when then the ambient temperature ($T_{ambient}$) is less than 16°C and cooling works if the ambient temperature is more than 21°C.

1. Passenger cars and vans. For heating and cooling, the cabin needs to be conditioned to an inside temperature of 21°C and then maintained at the same temperature. For conditioning, it was assumed that the heating/cooling works full blast for the first 5 minutes to get the cabin to temperature, if the ambient temperature is below 11°C or over 26°C. The power needed for that was assumed to be 2 kW.
    a. For conditioning:
    $$Cooling\ power\ [kW] = 2$$
    $$Heating\ power\ [kW] = 2$$
    b. For maintaining:
    For temperature difference up to 14°C:
    $$Cooling\ power\ [kW] = 0.0257 * (T_{ambient} - T_{inside}) + 0.1128$$
    $$Heating\ power\ [kW] = 0.0189 * (T_{inside} - T_{ambient}) + 0.0806$$

59 Evtimov, I., Ivanov, R., Sapundjiev, M., Energy consumption of auxiliary systems of electric cars, MATEC web of conferences 133, 06002 (2017).

For temperature difference above 14°C:

$$Cooling\ power\ [kW] = 3.33e^{-4} * (T_{ambient} - T_{inside})^{2.77}$$
$$Heating\ power\ [kW] = 2.44e^{-4} * (T_{inside} - T_{ambient})^{2.77}$$

2. Trucks: it was assumed that the power needed to maintain the cabin temperature would be 1.5 times that of the cabin of a passenger car or van. A similar case approach was considered as for passenger cars and vans for conditioning and maintaining. Thus the formulas are:
   a. For conditioning:

$$Cooling\ power\ [kW] = 2$$
$$Heating\ power\ [kW] = 2$$

   b. For maintaining:

For temperature difference up to 14°C:

$$Cooling\ power\ [kW] = 1.5 * 0.0257 * (T_{ambient} - T_{inside}) + 0.1128$$
$$Heating\ power\ [kW] = 1.5 * 0.0189 * (T_{inside} - T_{ambient}) + 0.0806$$

For temperature difference above 14°C:

$$Cooling\ power\ [kW] = 1.5 * 3.33e^{-4} * (T_{ambient} - T_{inside})^{2.77}$$
$$Heating\ power\ [kW] = 1.5 * 2.44e^{-4} * (T_{inside} - T_{ambient})^{2.77}$$

3. Busses: Because of the high capacity of people in the bus, it was not deemed necessary to condition the bus but only to maintain the temperature. Thus the formula for maintaining of temperature:

$$Cooling\ power\ [kW] = (636 * (T_{ambient} - T_{inside}) + 1400) / (2.5 - (T_{ambient} - T_{inside})/5 * 0.1)$$
$$Heating\ power\ [kW] = (636 * (T_{inside} - T_{ambient}) - 1400) / (3.5 - (T_{inside} - T_{ambient}) /5 * 0.1)$$

Note that the 1400 in the formula is the internal heat load by the passengers and driver in watt. The bus occupancy, averaged among the countries for which data was available[60], is 13. UNECE data leads to the same number[61].

For coaches the same was assumed, based on an average of 30% that is reported by EEA; the information is outdated though[62].

60 Eurostat PA_BUSCOA and TR_BUSCOA; https://ec.europa.eu/eurostat

61 UNECE, Bus and coach statistics TR.13 and TR.24, UNECE, for the year 2021, UNECE Transport Division; https://w3.unece.org/PXWeb2015/pxweb/en/STAT/STAT__40-TRTRANS__02-TRROAD/05_en_TRBUSCOACH_r.px/

62 EEA, long distance bus occupancy rates: https://www.eea.europa.eu/data-and-maps/figures/long-distance-bus-occupancy-rates, for years 2004-2008.

Appendix D: Energy flow graphs

This appendix shows the energy flow graphs for the LP10 archetype for the Amsterdam situation without PV, with PV on sun facing surfaces and with PV on all sides.

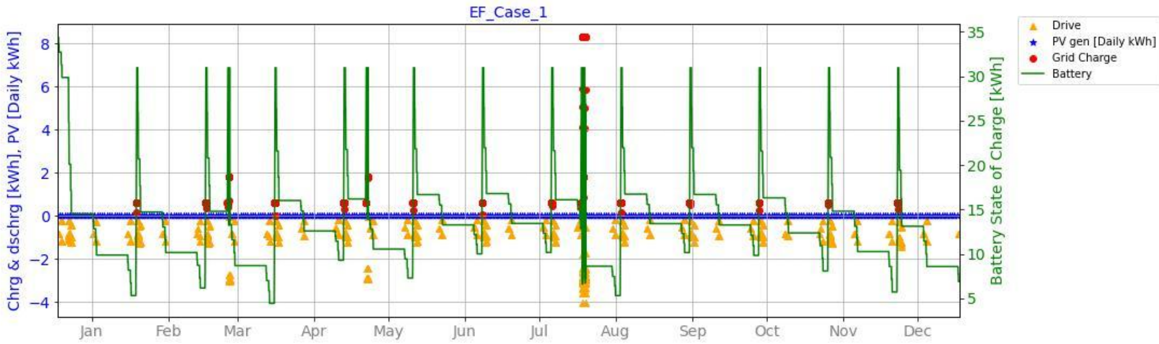


Figure 124: Energy flow for LP10 passenger car without PV using charging strategy A

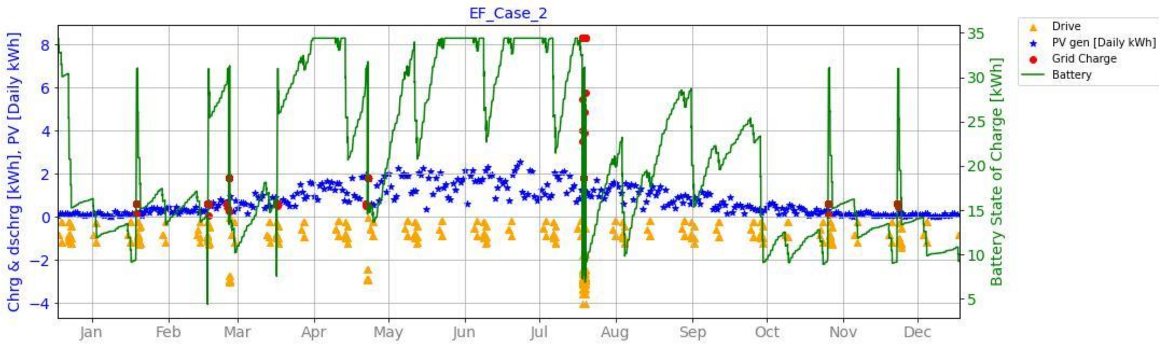


Figure 125: Energy flow for LP10 passenger car with PV on top using charging strategy A

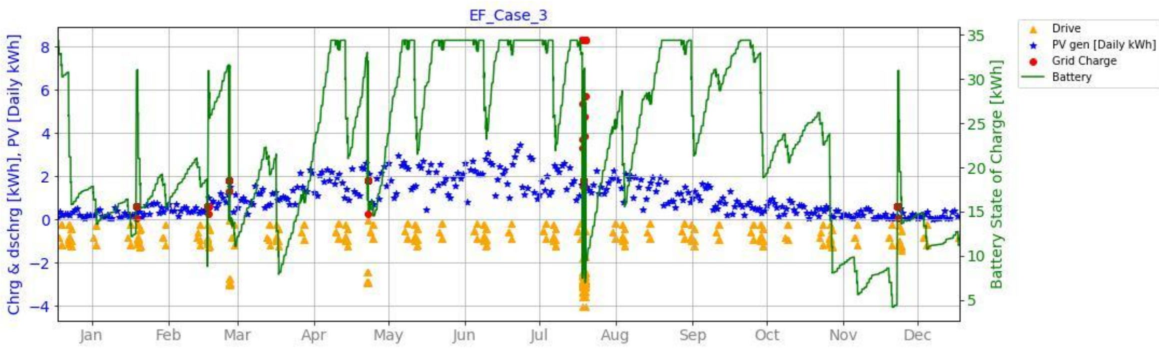


Figure 126: Energy flow for LP10 passenger car with PV on top and sides using charging strategy A

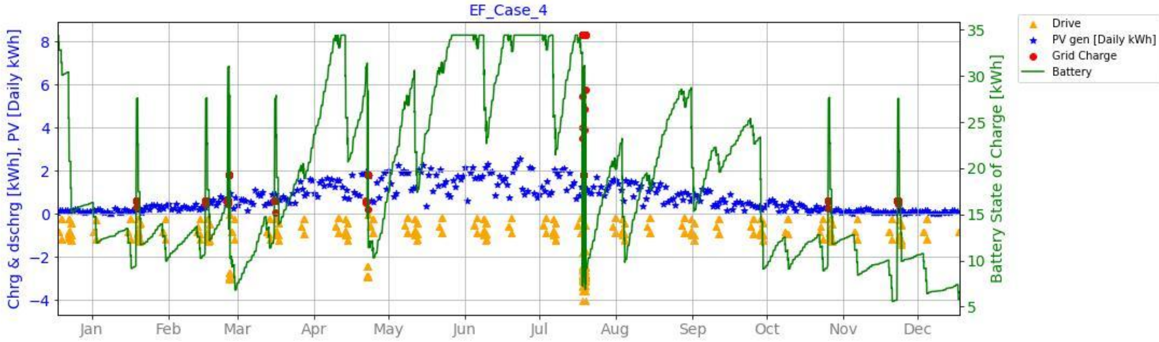


Figure 127: Energy flow for LP10 passenger car with PV on top using charging strategy .

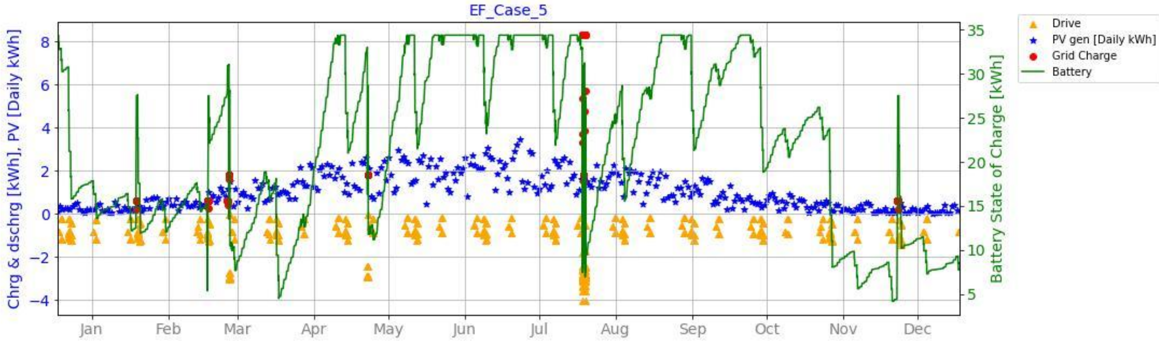


Figure 128: Energy flow for LP10 passenger car with PV on top and sides using charging strategy .

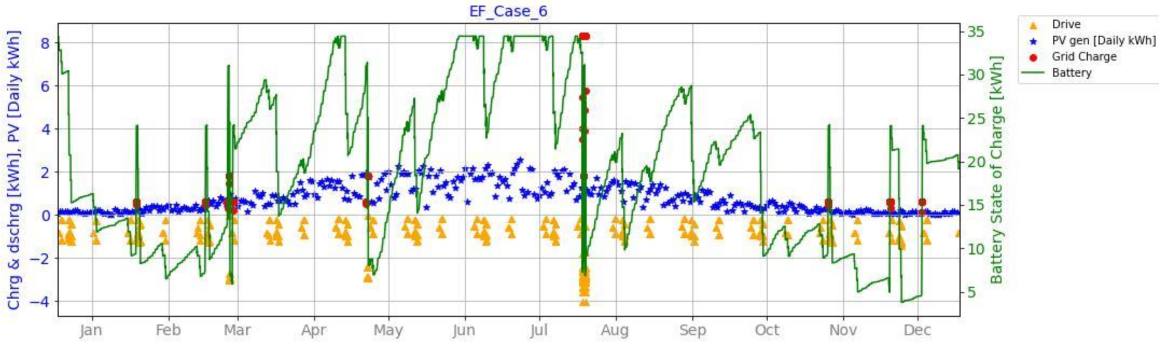


Figure 129: Energy flow for LP10 passenger car with PV on top using charging strategy C

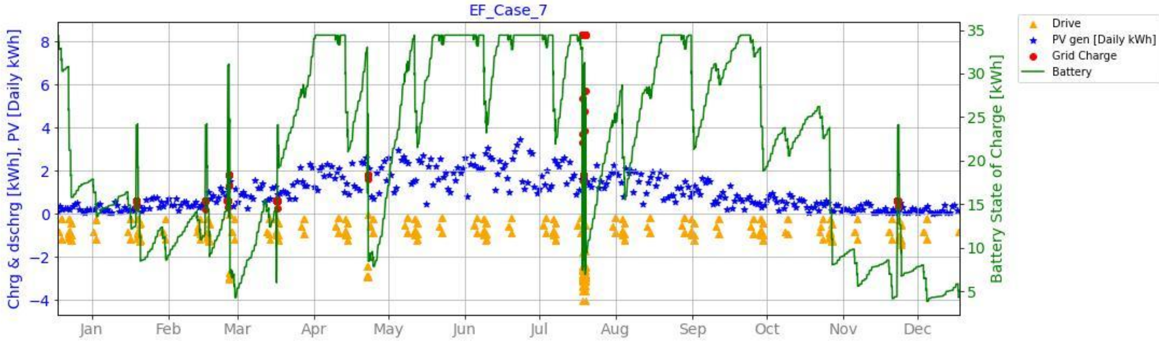


Figure 130: Energy flow for LP10 passenger car with PV on top and sides using charging strategy C

Appendix E: Zero-charging frequencies

Table 81: Zero-charging frequencies impact comparison of installing solar panels on cars for charging strategy A in an urban neighbourhood (Amsterdam, the Netherlands) comparing different seasons

Seasons	Percentage zero charging no PV	Percentage zero charging roof PV	Percentage zero charging roof and side PV
Winter	90.29%	91.20%	91.82%
Spring	89.93%	93.61%	95.13%
Summer	91.26%	95.01%	95.82%
Fall	90.32%	91.18%	91.71%

Table 82: Zero-charging frequencies impact comparison of installing solar panels on cars for charging strategy A in an urban neighbourhood (Amsterdam, the Netherlands) comparing different part of the day.

Day parts	Percentage zero charging no PV	Percentage zero charging roof PV	Percentage zero charging roof and side PV
Day (08:00-16:00)	97.44%	98.41%	98.67%
Evening (16:00-00:00)	80.50%	85.02%	86.53%
Nights (00:00-08:00)	83.87%	87.57%	89.28%

Table 83: Zero-charging frequencies impact comparison of installing solar panels on cars for charging strategy A in an urban neighbourhood (Amsterdam, the Netherlands) comparing weekdays and weekends

Day types	Percentage zero charging no PV	Percentage zero charging roof PV	Percentage zero charging roof and side PV
Weekdays	89.64%	91.88%	92.53%
Weekends	72.17%	79.12%	81.95%

Table 84: Zero-charging frequencies impact comparison of installing solar panels on cars for charging strategy A in an urban neighbourhood (Amsterdam, the Netherlands) comparing work weeks and holiday weeks

Seasons	Percentage zero charging no PV	Percentage zero charging roof PV	Percentage zero charging roof and side PV
Work week	68.41%	75.84%	78.83%
Holiday week	93.40%	95.16%	95.65%

Appendix F: Total cost of ownership

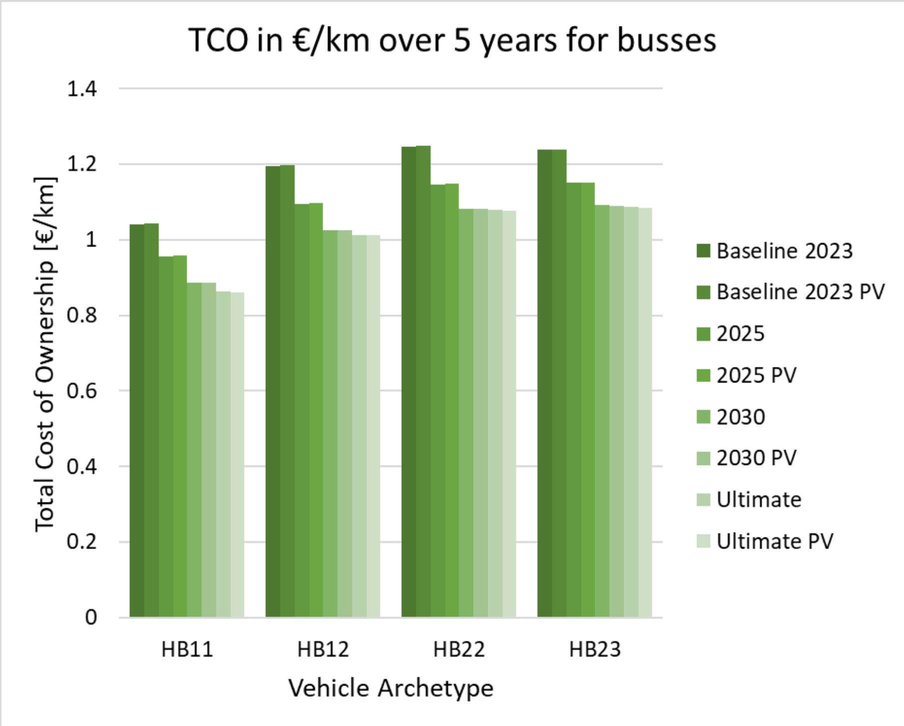


Figure 131: Total cost of ownership in euros per kilometre for different bus archetypes and different scenarios based on their efficiency improvements for an ownership of 5 years

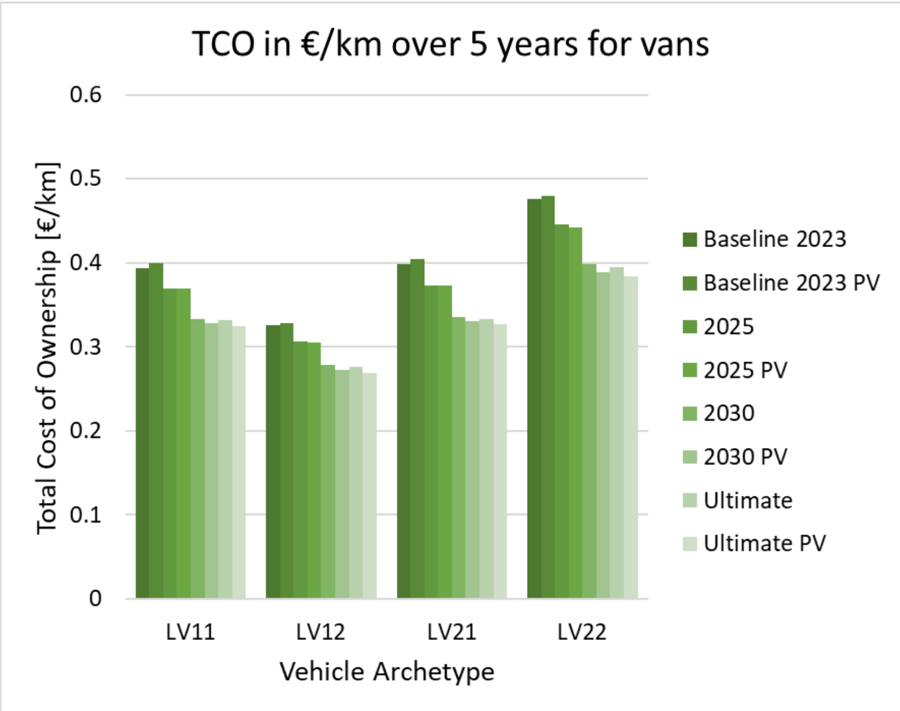


Figure 132: Total cost of ownership in euros per kilometre for different van archetypes and different scenarios based on their efficiency improvements for an ownership of 5 years

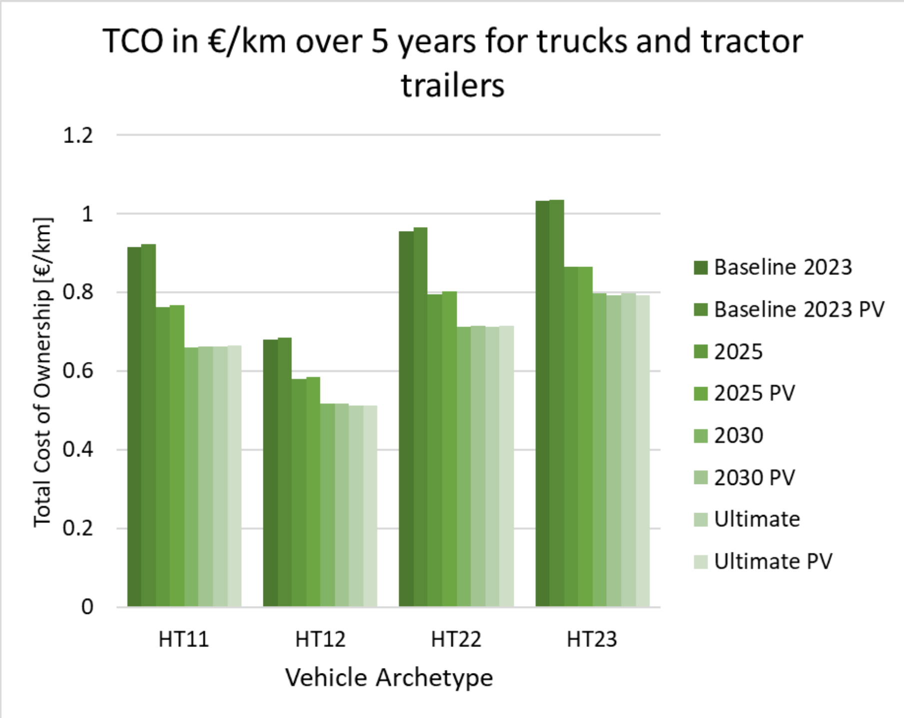


Figure 133: Total cost of ownership in euros per kilometre for different truck and tractor archetypes and different scenarios based on their efficiency improvements for an ownership of 5 years

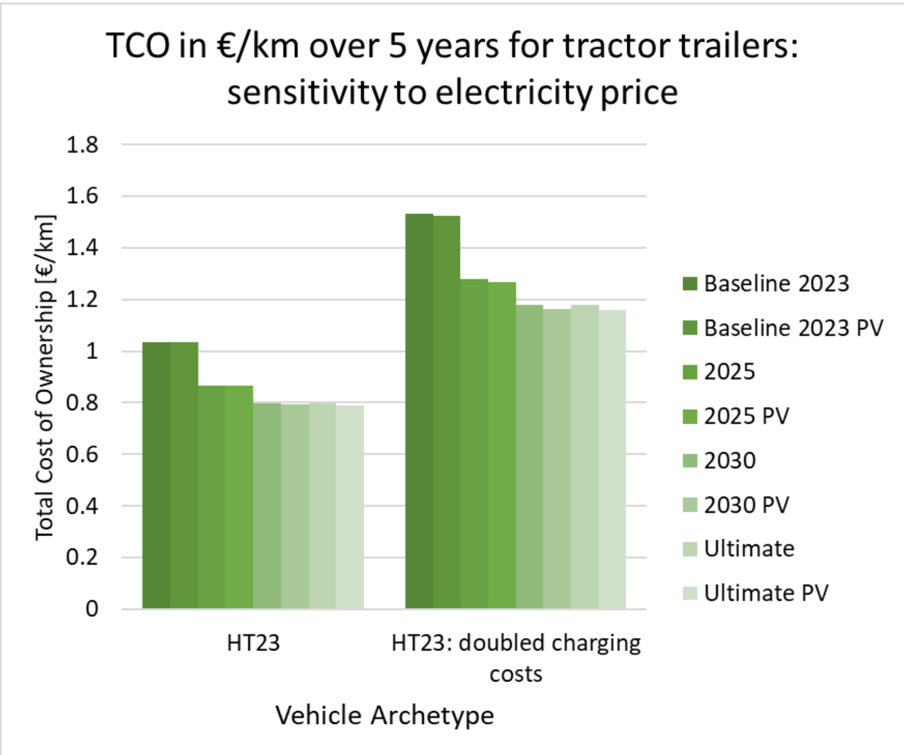


Figure 134: Total cost of ownership in euros per kilometre for long-haul tractor trailer for default and doubled charging costs, for an ownership of 5 years

Appendix G: Quality assurance procedures sensors

The units have been built with the experience Fraunhofer has for the calibration of solar reference cells. Therefore the construction allows for a recalibration of the reference cell. All units are being calibrated before the end control procedure. The calibration is being done in the certified Fraunhofer calibration lab CALLAB using the direct cable connection accessible when the unit is opened. After the calibration procedure the results of the process (calibration factor) is being used to calibrate the electronic signal amplification board to guarantee a standard signal output.

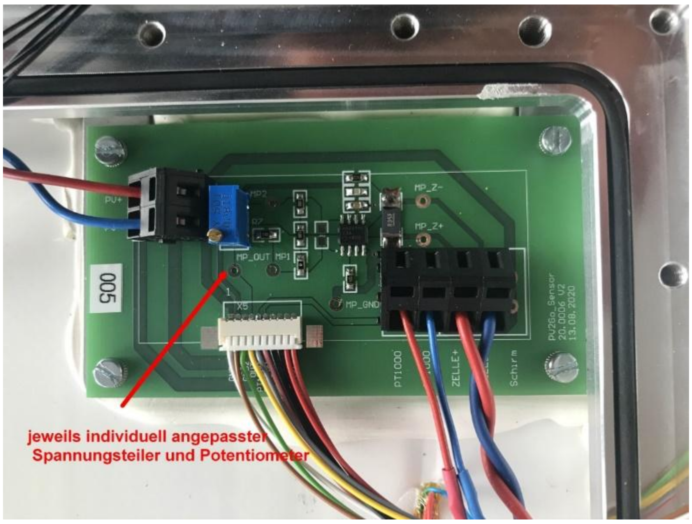


Figure 135: Picture of signal amplification board

Table 85: Example of calibration result

Messprotokoll Protokoll:PV2Go

Datum: 10.08.2023
Auftragsnr. 23.0049
Filename: Messprotokoll_PV2_071
Prüfer: EG

Verwendete Messgeräte
Measurement instruments used

Ser. Nr.	Bezeichnung	Zertifikat Nr.	Kalibriert bis	Unsicherheit
YK0780	Metrahit x-tra	15080-01-01	Nov 23	max.: 45µV
7780009	5500A Calibrator	SA01150512	Mrz 25	max.:30µA

1. Messung Ausgangsspnnung

Rg= 50000/ ((U_out /(Rshunt * I_in)) -1)

Versorgungsspannung 3,3V

Rg= 2820 - 2902 Ohm
Vsoll= 18,73 - 18,23

R_{shunt}= 0,05 Ohm

Rg= 50000/(V-1)
V=1+50000/Rg

U_out = U_in*V
U_in = R_{shunt} * I_in

T: 22°C

I_in [mA]	U_in_rechnerisch [mV]	U_out [mV]	V_ist	Unsicherheit	
0	0	6,3	n.a.n	30,18µV	
100	5	94,5	18,900	30,18µV	
200	10	187,6	18,760	30,18µV	
300	15	280,7	18,713	30,18µV	
400	20	373,9	18,695	30,18µV	
500	25	467,0	18,680	30,18µV	
600	30	560,2	18,673	30,18µV	
700	35	653,4	18,669	30,18µV	
800	40	746,5	18,663	30,18µV	
900	45	839,7	18,660	30,18µV	
1000	50	932,9	18,658	30,18µV	
1072	53,6	1000,0	18,657	30,18µV	Kalibrierwert Zelle
1250	62,5	1165,8	18,653	45,08µV	
1500	75	1460,0	19,467	45,08µV	

After the calibration procedure the units are being mounted on test racks on the building roof of the institute for the verification of the irradiance measurement values.

A thorough end control is being performed before the delivery of the sensor units following these steps documented on unit #43:

1. Irradiance value validation through reference measurement

All units have gone through an extended reference unit validation process. For the example of sensor 43 you see a deviation of 1,31% averaged over a one day measurement period in the following picture:

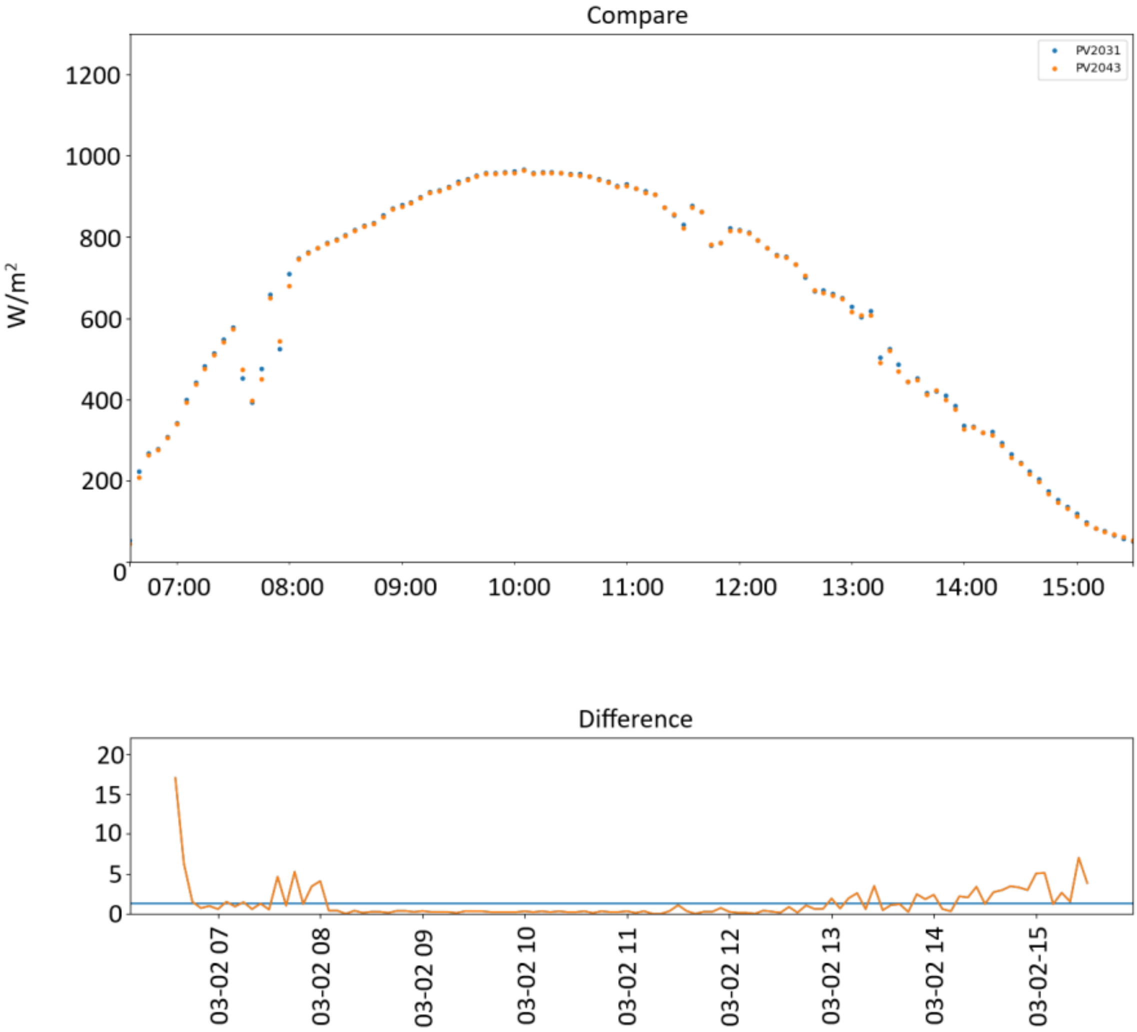


Figure 136: Example of reference unit irradiance comparison result 2.1.7

2. Validation of GPS Coordinates, cell temperature, measurement resolution change with drive modus & charge circuit control (Example of #43 in Freiburg).

The unit has been tested for availability of the data points: GeoCoordinates, T(cell), Battery voltage and the ability to switch the measurement resolution mode from “drive” to “stopped” (see red mark in Figure 44). Here the measurement resolution changes from 5 minute values in stopped state to 1s values in moving state.

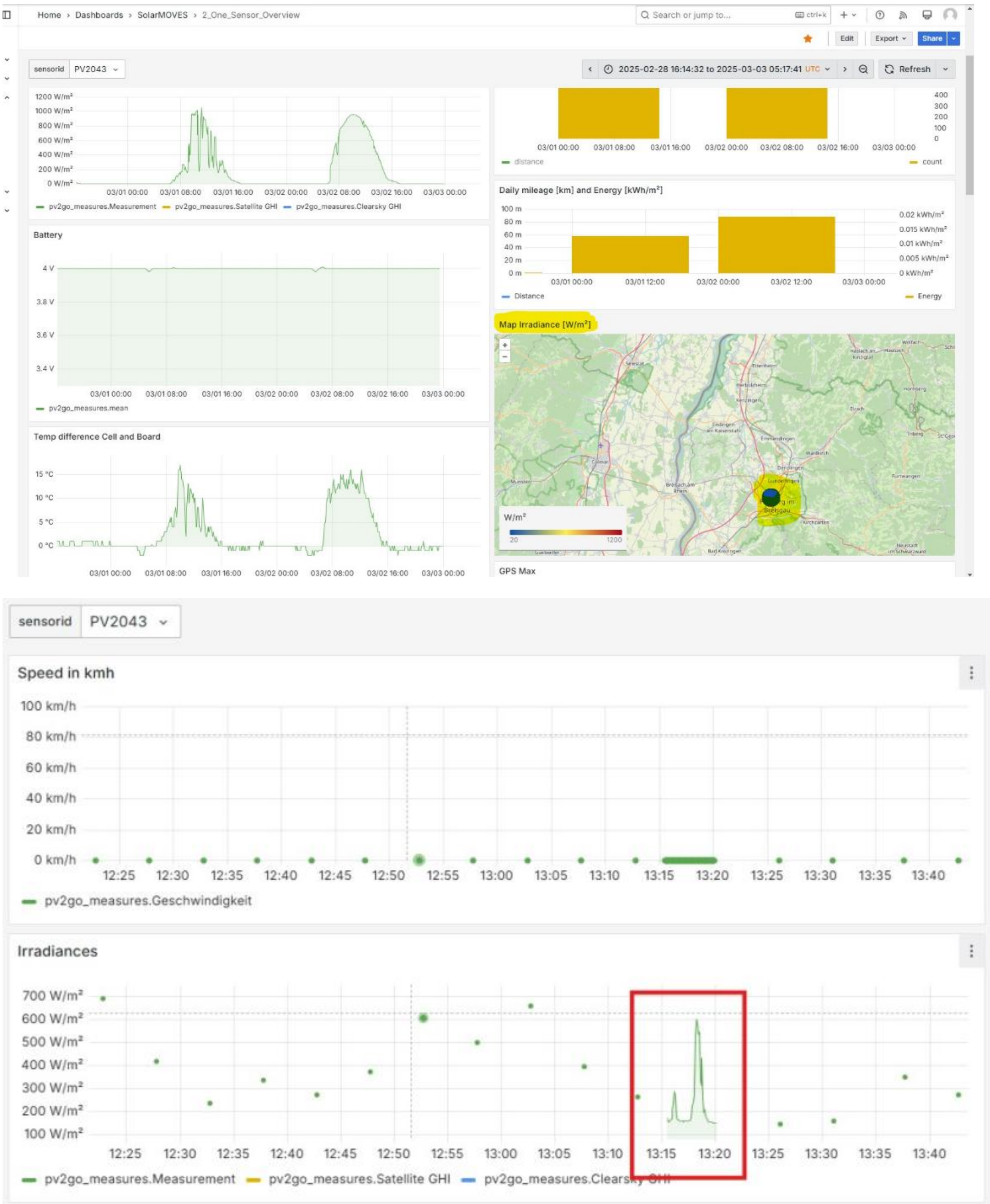


Figure 137: Example of reference unit drive state measurement resolution change.

SolarMoves

Fraunhofer ISE	Commissioning Protocol Solarmoves Sensor		
Data Acquisition			
Sensor ID	PV2043		
Sensor IMEI	355779549263119		
Data on Solarc server	☑ GPS Data	☑ Irradiance	☑ Cell temp plausible
Data check for 3 consecutive days before delivery	☑ Data Check		
Date / Tester	Moditya Gupta / Barbaros Inak		
Irradiation Data Reference Check (#31 or reference cell)			
Start time measurement	02.03.2025 06:00		
End time measurement	02.03.2025 15:00		
Comments			
	☑ sekündliche Messung		
Deviation	<3%		
Visual check		**Description/Date**	
Clean Glass	☐ Nein ☑ Ja		
Clean Silicone	☐ Nein ☑ Ja		
Clean Frame	☐ Nein ☑ Ja		
Visable damage	☑ Nein ☐ Ja		
Legs secured	☐ Nein ☑ Ja		
Restart & Error check	☐ Nein ☑ Ja		
Parameter Check	☐ Nein ☑ Ja	06.03.2025	
Lid for outside plug	☐ Nein ☑ Ja		
Outside plug tightened	☐ Nein ☑ Ja		
Other Comments			

Figure 138: Quality protocol before delivery of sensor unit

Appendix H: Sensors position on vehicles

IM Efficiency

The fleet from IM Efficiency comprises of ten vehicles representing both commercial and passenger vehicle archetypes. Each vehicle in the fleet is equipped with a minimum of 1 sensor and up to a maximum of 5 sensors per vehicle. Each sensor is strategically positioned to capture irradiance across different angles and orientation. Table 86 below gives an overview of the sensors and vehicles in the fleet.

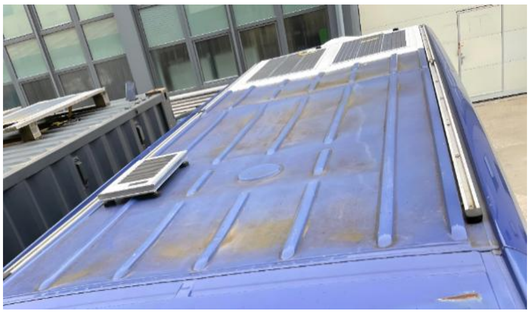
Table 86: Vehicle archetypes and sensor positions: IM Efficiency. The vehicle indicated in green is the electric truck for which the state of charge of the battery is available

Vehicle Type	Sensor: Total 18	Archetype	Images
IME, Renault Clio Bonnie (top)	1x roof	LP32	
IME, Renault Clio Clyde (top)	1x roof	LP33	
Peugeot Boxer Luton (Obelix)	1x roof 2x side	LV22	
E-Volvo truck	1x roof 2x side	HT22	
Scania Rigid truck	1x roof	HT12	 
DAF Rigid truck	3x roof	HT23	 
DAF Garbage truck 1	1x roof 4x side	HT11	
DAF Garbage truck 2	1x roof	HT11	

Sono Motors

Sono Motors has deployed ten vehicles equipped with irradiance sensors:

Table 87: Vehicle archetypes and sensor positions: Sono Motors

Vehicle Type	Sensor	Archetype	Images
Bus	8 x roof	HB11, HB12	
Van	1 x roof	LV21	
Passenger Car	1 x roof	LP21, LP22, LP23	

Lightyear

Lightyear has deployed five vehicles equipped with irradiance sensors. Sensors are marked in yellow:

Table 88: Vehicle archetypes and sensor positions: Lightyear

Vehicles	Sensor	Archetype	Images
Volkswagen Crafter	1 x Top 1 x Side	LV22	
Lightyear 0	1 x Front window	LP22	
Tesla Model 3	1 x Top	LP23	
Trailer till Jan-2025 (now removed, shipped to Barcelona for installation on RV)	1 x Top	LV22	
Total	**5**		

Note that the assigned vehicle archetypes are based on the most closely related archetype during the measurement period. In none of the cases there is an exact match between the archetype and the actual driving pattern of the vehicle. As a result, the assigned archetype is subjected to change.

Appendix I: Quality Assurance Procedures data

I1 Data cleaning procedure

Data filters and preparation for data base for evaluations

The first step in the data quality control process is loading data from various sensors to the connection server. Once the data is loaded, it undergoes parsing and formatting. During this stage, raw data is converted into a structured format. Any discrepancies related to datetime formats and GPS coordinates are corrected to maintain consistency and accuracy in the dataset.

Data cleaning is a crucial phase where outliers in the dataset are identified and filtered out. Specifically, outliers in the Irradiance, Speed, Latitude, and Longitude columns are examined and removed.

The data poses several inherent errors, data point adjustments due to in-field efficiency requirements such as:

- Data inconsistencies due to incorrect future dates.
- Longitude and latitude as N,S,E and W instead of positive and negative points.
- Longitude and latitude set to 0 when the vehicle is not moving.
- Other erroneous locations outside of operation area.

To eliminate and filter the data, a complete Python package named Solar Moves Python (SoMopy) was developed. Through several steps, the scripts in SoMopy eliminates these inconsistencies and errors.

1. Firstly, the script fills the missing sensor names in dataset where it is missing.
2. Wrong irradiance sensor readings are removed by keeping only values below 2000 W/m^2.
3. Readings lower than 5 W/m^2 are set to 0 to eliminate noise from night time measurements.
4. After cleaning irradiance data, only entries with valid speed values are retained — specifically speeds between 0 km/h (inclusive) and 200 km/h (exclusive).
5. Longitude, latitude values equal to 0 are replaced with NaN. Additional filter removed faulty location readings. If a faulty reading was taken, the reading starts with 'e', which is also filtered out.
6. A geographical bounding box for Europe is applied to the data frame to eliminate incorrect recorded longitude and latitude values that fall outside the valid region. A final median filter filters out unrealistic jumps in the location readings, using a tuneable threshold within an hourly range.
7. Data points are grouped by hour, and any longitude or latitude values differing by more than 1° from the group's median values are discarded.

I2 Data visualization

Data from the server is regularly pulled using a cronjob at Fraunhofer ISE. This data is then filtered and stored. This data also updates a master excel sheet at Fraunhofer '**Status**', where information about the last data sent, etc. The status sheet as shown below helps keep track of all the sensor locations, when they last sent, and to which date the last sent data belongs. If any sensors do not send values in the last 5 days, it is discussed in the meetings with Partners. Colour codes are given according to when the data was last sent:

This excel file also has another sheet, which is maintained regularly in case any operations are carried out on the sensors. This sheet is called the **'Logbook'.** Any operation done on the sensors, including physical examinations to debugging, mounting dismounting are noted down in the sheet. This helps keep track of all the sensors. The Status sheet mentioned in the last picture is also updated based on this logbook automatically.

Appendix J: Satellite Derived Solar Irradiance

The Heliosat method is an empirical approach for deriving solar irradiance from satellite imagery. In this case from Meteosat Second Generation (MSG) satellite images provided by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)[63]. The Heliosat method relies in particular on the High Resolution Visible (HRV) channel with wavelengths in the visible light range of the spectrum between 500-900 nm.

A general overview of the approach is as follows[64]:

1. **Satellite Image Collection:** HRV images are obtained from MSG satellites, the images are transmitted every 15 minutes, with a resolution of approximately 1 pixel per square kilometre in Europe. Clouds are represented as brighter regions against the darker surface of the Earth.

2. **Calculate Reflectivity Values**: The maximum and minimum reflectivity is derived from a month's worth of previous satellite images, for that time slot during the day. The maximum reflectivity represents the brightest cloud cover, while the minimum reflectivity represents the reflectivity of the ground under clear sky conditions.

3. **Calculate Cloud Index**: For each pixel, in the image a cloud index is calculated. This is a measure of sunlight obstruction by clouds. The reflectivity of each pixel is compared with reference values of the maximum (cloud) and minimum (ground) reflectivity to derive the cloud index.

   $$n = \frac{\rho - \rho_{\text{ground}}}{\rho_{\text{cloud}} - \rho_{\text{ground}}}$$

   where, n is the cloud index and ρ is the reflectivity.

4. **Calculate Global Irradiance**: Finally, the global irradiance is calculated. The cloud index is subtracted from 1 to get the clear sky index which is then multiplied with a clear sky model to get the global irradiance value. The clear sky model is a representation of the atmospheric parameters and sun elevation under cloudless conditions.

   $$G = (1 - n) \cdot G_{\text{clearsky}}$$

   where G is the global irradiance and G_{clearsky} is the clear sky irradiance.

The Heliosat method provides a means for estimating solar irradiance, which is crucial for the efficient planning and operation of solar energy systems. When applied with MSG imagery a high temporal frequency of 15 minutes and a spatial resolution of 1 km² is obtained, giving the method a wide range of applications.

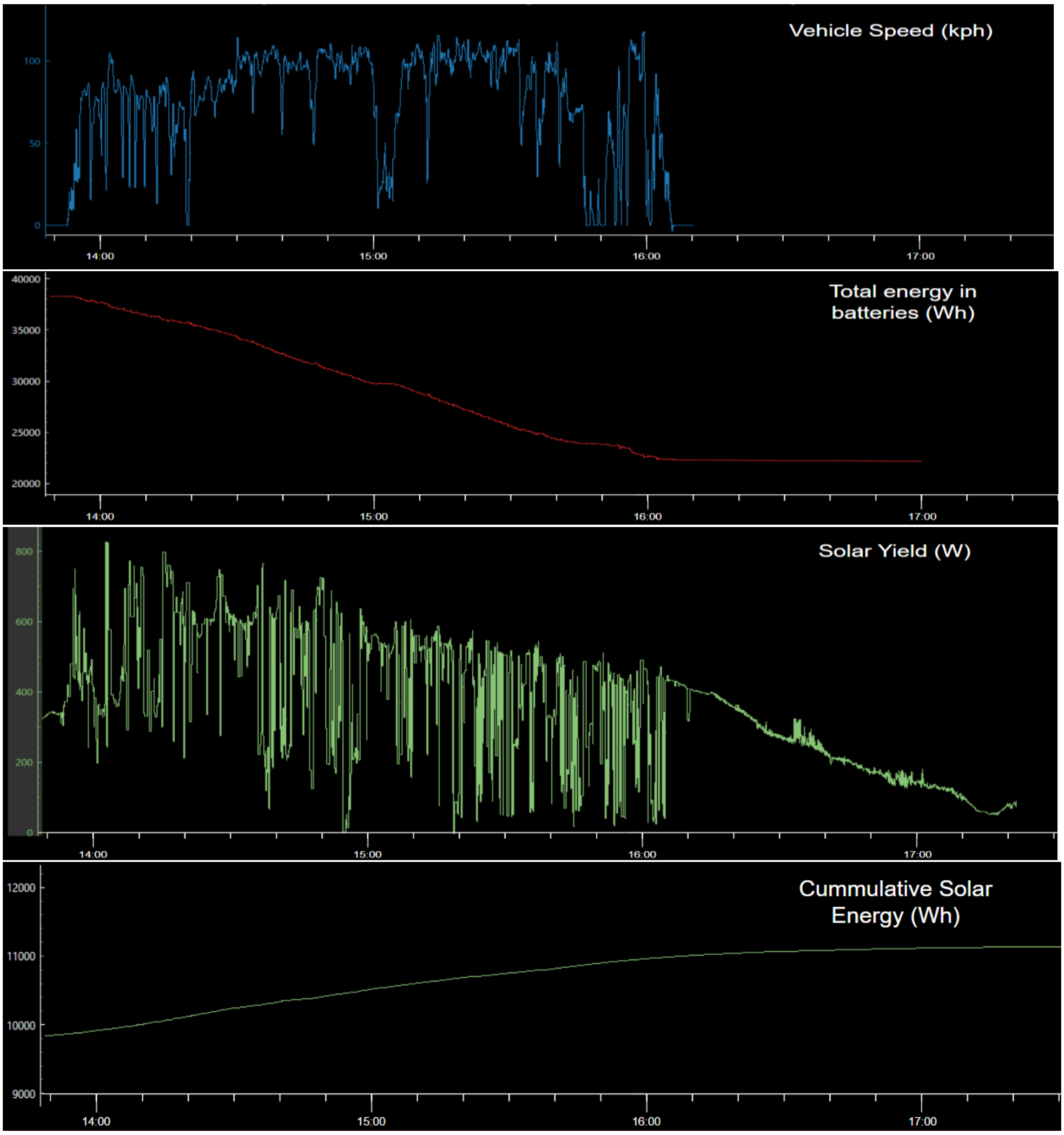
[63] EUMETSAT. (n.d.). Meteosat Second Generation satellite imagery. https://www.eumetsat.int/meteosat-second-generation

[64] Hammer, A., Heinemann, D., Hoyer, C., Kuhlemann, R., Lorenz, E., Müller, R., & Beyer, H. G. (2003). Solar energy assessment using remote sensing technologies. Remote Sensing of Environment, 86(3), 423-432. https://doi.org/10.1016/S0034-4257(03)00083-X

Appendix K: Data buildup Lightyear 0 measurement campaign

The example below illustrates data captured during the longest recorded drive with the Lightyear 0, highlighting four key parameters: the vehicle's speed profile, total battery energy, and solar power generation including cumulative solar yield.

During this afternoon drive (13:45–17:30), the vehicle covered 163 km (odometer reading), consuming a total of 15.94 kWh of gross energy. Over the same period, the integrated solar array contributed 1.15 kWh of harvested energy. During driving, it can also be clearly seen that solar is more dynamic than stationary, which is primarily attributed to dynamic shading effects from the car moving compared to the surrounding environment.



Appendix L: Sono Motor Measurement Parameters

For each test drive, the following data parameters were collected and have been shared with the EC:

Table 89: E-Van Vehicle Data

Vehicle	
Ignition	• Ignition_Status
State of Charge	• SoC
Battery	• Battery_Voltage_LV • Battery_Voltage_HV • Battery_Current_HV
Charging	• AC_Slow_Charge_Voltage • AC_Slow_Charge_Current • DC_Fast_Charge_Voltage • DC_Fast_Charge_Current
Speed	• Vehicle_Speed

Table 90: Onboard Solar System Data

Solar System	
Voltage	• Solar_VOut_HV • Solar_VOut_LV
Power	• Solar_POut_HV • Solar_POut_LV
Location	• Latitude • Longitude • Altitude

Appendix M: IM Efficiency: Case study regional Garbage truck

Figure 139 illustrates the regional garbage truck, equipped with one roof sensor and four side sensors mounted on the upper and lower sections of the left and right cabin walls. The picture emphasises that, unlike the horizontal roof sensor which receives a large portion of the irradiance most of the time, the vertical side sensors experience strong dependence on ‘where’ they are positioned on the side wall apart from sun position, vehicle orientation and shading from surrounding buildings and the truck body itself.

Figure 139: Schematic picture (left) and photo (right) of the sensor location on the DAF garbage truck

Due to the operational nature of garbage trucks, the vehicle is driven almost continuously during collection shifts, which has resulted in a very large dataset from all five sensors. However, intermittent connectivity issues in the Netherlands have caused data preventing a fully consistent timeline comparison for the entire measurement period. For this reason, the analysis in this paragraph combines the data from two different periods of the same side (left side) of the truck. The data for left top sensor is between 21/10/2024 and 30/10/2024 while the data from left bottom sensor is between 31/01/2025 and 04/02/2025. Therefore, the measurements from the two periods are interpreted as two separate but comparable samples of how the upper and lower halves of the left side of the truck respond to solar irradiance under typical garbage collection conditions in Limburg region of the Netherlands. The October 2024 dataset represents late autumn conditions for the left top sensor, while the January–February 2025 dataset represents midwinter conditions for the left bottom sensor, both on the same kind of stop and go urban driving and frequent shading from buildings and the truck body conditions. This means the comparison is not a strict time aligned day-by-day comparison, but a statistical comparison of distributions that shows how sensitive the two sensor positions are to geometry and shading.

The box plot in Figure 140 summarises the distribution of daily solar energy received by the left top and left bottom sensors over their respective measurement periods. The red line inside each box represents the median daily energy. For the upper sensor this is around 560 Wh/m², whereas for the lower sensor it is only about 80 Wh/m², indicating that on a typical day the upper half of the side wall collects roughly an order of magnitude more energy than the lower half. The inter-quartile range of the top sensor (height of the blue box) spans roughly 70–760 Wh/m², showing large day to day variability driven by cloud cover and how often the truck is exposed to open sky, while the lower sensor's box (orange box) is much narrower and clustered near low values, reflecting that the lower half is much more often in shade or only receiving diffuse and reflected light. The fact that the lower sensor still has a maximum daily energy comparable to the upper sensor (whisker extending to about 830 Wh/m²) demonstrates that, on rare days when the geometry is favourable and shading is minimal, the bottom half can momentarily receive nearly as much irradiance as the upper half, but such conditions are clearly not the normal.

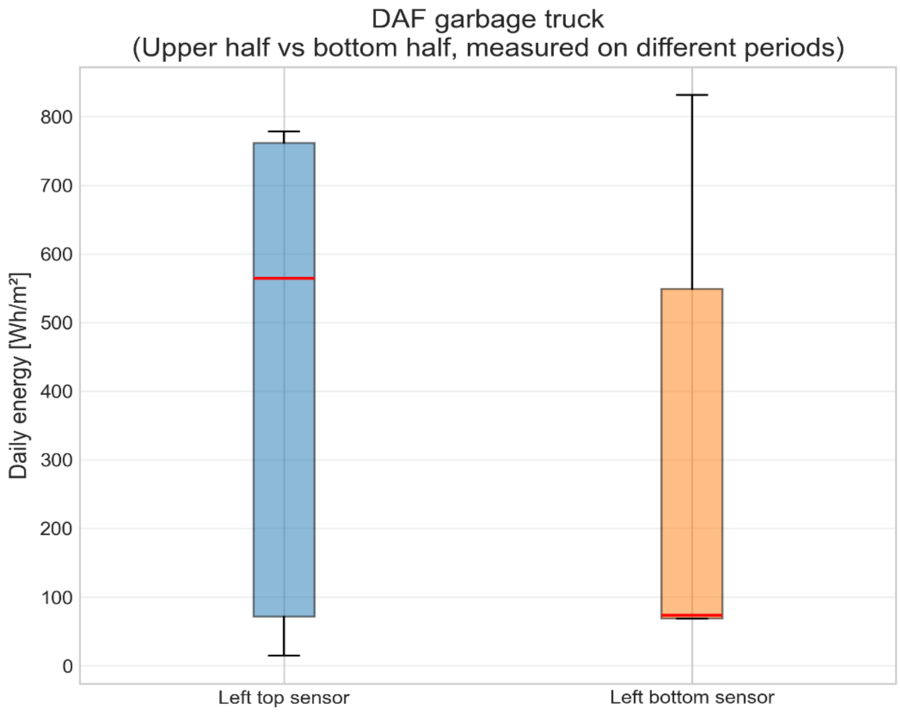


Figure 140: Box plot showcasing the left side sensor data for different periods

From a practical standpoint, this behaviour is consistent with studies on BIPV studies in an urban environment. Chatzipoulka et al. [65] demonstrated an almost direct linear relationship between 'sky view factor' and annual global irradiance for multiple European cities which show that the upper parts of a wall in a building have a larger 'sky view factor' and receive more direct beam radiation, while the lower parts are more heavily influenced by obstruction and only receive a combination of diffuse and ground reflected irradiance. Applying this logic to the DAF garbage truck, the upper side sensor is mounted higher on the cabin wall and has better chances to capture direct sunlight for longer periods, whereas the bottom sensor is closer to the road level and more frequently

[65] Christina Chatzipoulka, Raphaël Compagnon, Jérôme Kaempf, Marialena Nikolopoulou, Sky view factor as predictor of solar availability on building façades, Solar Energy, Volume 170, 2018, Pages 1026-1038

shaded by the cargo box, cab geometry and surrounding urban objects. Though the distance is small in this application the logic remains the same. Therefore, we could consider that the upper half of the cabin typically receives 60–75% of the annual vertical irradiance while the lower half receives 25–40%, even though both halves can experience similar peak irradiance under rare, unshaded conditions. This conclusion can be further validated in the future when the sensor data has been retrieved and the irradiance data recorded on same days of the year for the sensors are compared.

Appendix N: Policy recommendations supporting information

N1 Interview protocol

Interview Protocol: The Impact of Integrating PV on Vehicles

Introduction (max. 5 min.)

1. **Purpose:** the aim of this interview is to explore the perspectives of various stakeholders regarding the integration of PV into vehicles. We want to get a better understanding of what effect the adoption of VIPV has, both on a vehicle or fleet level and a societal level.
2. **Confidentiality:** As part of our research, we would like to include the insights from this interview, along with your name and organization, in the appendix of the final report. However, we completely understand if you would prefer not to have this information shared due to privacy concerns or the sensitivity of the topics discussed. Please let us know your preference, as your comfort and confidentiality are important to us. Do note that the results will only be used for research purposes.
3. **Duration:** This interview will take approximately 1 hour.

General questions for all stakeholders (30 min.)

- What do you think is the added value of VIPV?
- What is the role of your organization within the value chain of VIPV?
    - Do you take a more active or passive role?
    - Who are your most important partners within the value chain?
    - Do you also collaborate with parties outside of the value chain, such as government bodies, research institutions?
- What motivates your organization to support or consider the adoption of VIPV technology?
- In your opinion, what are the main benefits of integrating PV into vehicles?
- What do you perceive as the potential drawbacks or challenges of the adoption of VIPV?
    - Any bottlenecks in the supply chain (upstream/downstream)?
    - Do you see any potential solutions for these challenges?
- How important do you think solar-powered vehicles will be in the future of sustainable mobility?
- What do you think is the effect of VIPV on infrastructure (electricity in general and charging infrastructure more specifically)?

Questions for passenger / light vehicle VIPV manufacturers (20 min.)

7 What technological challenges do you foresee in integrating PV into vehicles?
8 What are financial implications of producing cars with VIPV? Would this impact economic viability significantly?
9 How do you see consumer demand for VIPV evolving in the next 5-10 years?
9.1 Which consumer groups are most relevant?

Questions for heavy duty vehicle VIPV manufacturers

10 What is the main reason why fleet operators decide to purchase VIPV from your company?
11 What are the key advantages of your VIPV technology on trucks?
11.1 How does integrating your panels impact truck performance, including energy efficiency and aerodynamics?
12 What cost savings or ROI can fleet operators expect from adopting this technology?
13 What challenges should operators consider regarding durability, maintenance, or installation?

Questions for Government/Policy Makers

14 Do you think governments should stimulate the adoption of VIPV?
15 What, if any, do you think are the main challenges that potentially hinder large-scale adoption of VIPV?
16 What role could governments play in alleviating the challenges that hinder large-scale adoption of VIPV?
17 What incentives or policy measures do you think should be in place to encourage the adoption of solar-powered vehicles?
18 What role do you see for governments in promoting research and development in this area?
19 Are there any regulatory barriers or challenges you foresee in the widespread adoption of solar-powered cars?

Conclusion:

Closing Questions:

1. Is there anything else you'd like to add regarding the potential of solar panel integration in cars, or any aspects we may not have covered in this interview?
2. Do you have any recommendations of who else or which party is important/relevant for us to speak to? Do you have any contact details?
3. Do you have any quantitative data that would be relevant for us to have, such as cost figures, benefit figures, technical data? Would you be willing to share that at a later date?

Thank you for your time and insights. Practicalities:

1. We will ask you to review our summary of your responses and let us know if any adjustments are necessary.

N2 Summaries of interviews

N2.1 Interview with Sono Motors

Sono Motors is a provider for solar integration products for the commercial vehicle and automotive industry. Previously, Sono Motors was aiming to develop a passenger car with integrated PV, but now it focuses on buses, trucks and vans. Customers are both in the after sales market and OEMs. The interviewee is a representative of the company.

What do you think is the added value of VIPV?

VIPV offers significant value by providing renewable electricity directly to vehicles, which results in lower operating costs and reduced emissions.

In your opinion, what are the main benefits of integrating PV into vehicles?

Different use cases for VIPV exist, such as applications in commercial vehicles – trucks and buses – or passenger vehicles. Benefits vary per use case. In general, the following benefits are applicable:

Main reasons:

- **Reduced operating costs (TCO)**: by generating a share of their own energy, vehicles with integrated solar panels can reduce their fuel or electricity expenses. Over time, the savings on energy costs can offset initial investment costs.
- Other reasons:
- **Emission reduction / sustainability**: VIPV can lead to emission reduction by ensuring a share of the energy consumed by the vehicle has a renewable origin. It could help manufacturers or fleet operators comply with stricter EU emission regulations. Especially in cities there is a policy focus on mandatory CO_2 reduction.
- **Reduce range anxiety**: for electric vehicles, VIPV can help extend the driving range by providing energy whilst driving. This can reduce range anxiety, a common concern among consumers.
- For commercial vehicles , an additional benefit can be identified:
- **Comfort**: a portion of commercial vehicles is also used for overnight stays of the driver. VIPV enhances the comfort of these overnight stays by providing a reliable power source for auxiliary systems, like air conditioning, heating and lighting. This means that the driver can maintain a comfortable cabin temperature without idling the engine, reducing both noise and emissions.

What do you perceive as the potential drawbacks or challenges of the adoption of VIPV?

Again, the challenges related to the adoption of VIPV depend on the vehicle type. For passenger vehicles, the challenges are more significant compared to commercial vehicles, like buses or trucks. First of all, the surface area which could be used for solar panels in passenger vehicles is relatively small compared to, for example, trucks. This limits the amount of energy that can be generated and therefore might affect economic viability. Second, engineering challenges persist as the design must ensure PV does not compromise the vehicle's aerodynamics or aesthetics. Third, there is a reluctancy for customers to put down the extra upfront CAPEX. Regulatory interventions are typically aimed at CO_2 reduction targets, and there are no additional credits for the customer compared to EVs without VIPV. Ultimately, the market for VIPV in passenger vehicles is still in its early stages and more widespread adoption would take time.

An additional remark is that total grid-independency will always remain a challenge. However, technological developments are such that VIPV will achieve some market share.

For commercial vehicles, the concerns on limited service area or engineering challenges are not as present. Solutions for trucks or buses are readily available, as offered by our company (Sono Motors).

One key challenge that exists for any vehicle type is that there are regulatory barriers. Currently, there are no clear guidelines on how to quantify emission reductions as a result of solar panels on vehicles. Due to this, it is not possible to differentiate between electric vehicles with or without solar panels in terms of emission reductions.

What do you expect the role of VIPV to be like in the mid-term/long-term within mobility? What do you see as possible adoption scenario's?

I foresee a gradual but significant adoption of VIPV over the mid- to long term. Currently, we are still in the early adopter phase. In the mid-term (2030), I expect there to be a substantial uptake of VIPV in the commercial sector. As discussed previously, commercial vehicles, such as buses, have a larger surface area and are therefore more suitable for solar panel integration. This results in higher energy generation, which can be used to power auxiliary systems and reduce fuel consumption.

As a result of this gradual adoption, I foresee that by 2040 a significant portion (>50%) of commercial vehicles will be equipped with VIPV, driven by the need to reduce operating costs and comply with stricter emission regulations. For passenger vehicles, the adoption rate will likely be lower, but as production costs decrease and benefits become more apparent, VIPV in passenger vehicles could still play a significant role, though the adoption rate for this vehicle type remains more uncertain.

What do you think is the effect of VIPV on infrastructure (electricity in general and charging infrastructure more specifically)?

VIPV could have a significant impact on the need of additional electricity infrastructure by decentralizing energy generation.

VIPV would reduce the dependency on charging points. This could be especially valuable in densely populated areas, where there is limited space available for charging points.

VIPV reduces the dependency on charging infrastructure and the electricity grid by generating energy directly on the vehicle. This decentralization of energy generation eases the needed infrastructure capacity, which could be particularly relevant for densely populated areas, where limited space is available for charging points. As a result, VIPV could reduce required investments in infrastructure.

N2.2 Interview with Lightyear

Lightyear is a company offering solar charging systems for passenger vehicles. The interviewee is a representative of the company.

What do you think is the added value of VIPV?

First, VIPV is 'nice to have' rather than a 'must have' for EVs. The added value of VIPV lies in providing a solution for people who want to own an electric vehicle but find charging it challenging. VIPV gives users more control over how and where they charge their vehicle, which is particularly useful for those living in apartments without easy access to charging points. Additionally, VIPV can reduce emissions from transportation with the energy being produced in the very place it is used.

The business case for VIPV for the end user is positive, if you put a value on the increased convenience and autonomy. This holds also for different European countries, e.g. Spain and the Netherlands, because the difference in irradiation is offset by a difference in electricity prices.

In your opinion, what are the main benefits of integrating PV into vehicles?

There are several benefits related to VIPV in passenger vehicles, of which the below are a few:

- **Reduced emissions:** the electricity provided by the solar charging system is fully renewable as opposed to electricity as provided by the grid.
- **Energy autonomy**: by placing solar panels on a vehicle, a significant proportion of the vehicle's energy needs can be met by the electricity generated by the solar panels.
- **Convenience & accessibility**: it enables users to make less use of public charging solutions making electric vehicles more accessible to a larger share of the population.
- **Extended battery lifetime**: there are indications that better temperature management (smaller bandwidth) of batteries, powered by integrated PV, can extend battery life by as much as 30%.
- **Lower operational costs**: reduced dependency on the electricity grid could reduce charging costs.
- **Acceleration of EV adoption** as it ameliorates or mitigates many of the current barriers given by consumers (lack of charging infrastructure, convenience, range limitations)
- **SolarMoves study** also indicates some situations where it relieves grid congestion issues, particularly in neighbourhoods with high EV penetration

What do you perceive as the potential drawbacks or challenges of the adoption of VIPV?

There are a few challenges that VIPV faces. First of all, a lot of private consumers are unaware of the benefits and potential of VIPV. The automotive industry tends to be a conservative industry, where car manufacturers are hesitant to be a first mover. In essence, this results in a chicken and egg dilemma. Who should get moving? Should this be consumers or the car manufacturers?

Fundamentally, governments can stimulate 'eco innovation' and make both of these groups move. If they see the added value of VIPV, they could help car manufacturers take the risk of integrating this new technology, e.g. through tax credits. For example, in South Korea, car manufacturers get paid for installing PV in their EVs.

In addition, the European Union has set a target that all vehicles sold in 2035 are zero-emission. To reach this target, EVs will have to be accessible to everybody. Government incentives will help to enable provision of solar powered vehicles to people with limited accessibility to charging stations.

What do you expect the role of VIPV to be like in the mid-term/long-term within mobility? What do you see as possible adoption scenario's?

It is difficult to make an estimate of what the adoption of VIPV would look like in the mid-term. This depends on whether and when the chicken and egg-dilemma in the automotive industry will be broken through. If there will be one car manufacturer who moves, the rest will follow swiftly. Government incentives could help bridge this gap and uncertainty.

However, in the long-term, by 2035 and beyond, I foresee that VIPV will become a standard feature in electric vehicles, especially as a result of the increased convenience and autonomy for EV owners.

On the side of all this, we are ready to scale-up our operations for widespread market adoption. So if car manufacturers decide to move, we do not see any bottlenecks in providing solar solutions on a market scale.

The incentive for policy makers to stimulate the adoption of VIPV is, as mentioned before, (1) to act as an additional stimulus to reach the 2035 zero-emission goal, and (2) to contribute to a solution for grid/charger congestion.

What do you think is the effect of VIPV on infrastructure (electricity in general and charging infrastructure more specifically)?

VIPV could help reduce the demand for electricity from the grid, especially during peak hours. By generating their own electricity, vehicles with VIPV can help balance the load on the grid and reduce the risk of grey outs.

Additionally, VIPV can help minimize charging congestion during peak hours (typically between 5-9 PM) by reducing the frequency with which vehicles need to charge. For example, if a vehicle with VIPV can generate enough energy during the day, it may only need to be charged every few days instead of daily. This can alleviate the pressure on public charging stations and make it more convenient for users to find available charging spots when needed.

N2.2 Interview with Fraunhofer ISE

The interviewee is a researcher at Fraunhofer ISE, with the focus on solar-energy applications.

What do you think is the added value of VIPV?

For now, I foresee the added value of VIPV mainly in fringe applications, such as trucks with large surface areas and small lightweight vehicles like tuktuks.

Large trucks have large surface areas, which provide ample space for installing solar panels. This large surface area allows trucks to capture more sunlight and generate a relatively large amount of energy. This energy can be used to power auxiliary systems like refrigeration units, reducing the reliance on diesel fuel and lowering operational costs.

For lightweight vehicles like tuktuks, their energy needs are relatively low compared to larger vehicles. Integrating solar panels into these vehicles can provide a substantial portion of their energy requirements, making them more efficient and reducing the need for frequent charging.

This is particularly beneficial in urban environments where these vehicles are used for short-distance travel.

For VIPV to have significant added value in standard passenger vehicles, the whole mobility sector will have to be fundamentally re-thought and restructured. Since this sector relies largely on legacy technology, VIPV is less straightforward here.

In your opinion, what are the main benefits of integrating PV into vehicles?

One of the key advantages of VIPV is not necessarily an advantage that is directly linked to the technology. However, it is indirectly linked to integrating solar panels into vehicles. VIPV forces the automotive industry to re-think the way mobility is designed and provides a push towards mobility with higher energy efficiency. Since the dawn of the automotive industry, there have not been any significant changes that positively affect energy efficiency. If vehicles are more energy efficient, VIPV can have a larger positive effect. Therefore, there is a stimulus to design vehicles with higher energy efficiency.

Next to that, for commercial vehicles, VIPV could help reduce the use of fossil fuels by providing energy for auxiliary systems. This leads to a reduction in emissions.

What do you perceive as the potential drawbacks or challenges of the adoption of VIPV?

One of the primary challenges of integrating solar panels into vehicles is its technical complexity. This is especially relevant for electric vehicles. The process requires sophisticated electronics and modifications to the vehicle's design. For instance, the vehicle needs to be equipped with DC-DC converters to manage the power generated by the solar panels and feed it into the battery.

A challenge for passenger cars specifically is the available surface area. This limitation means that the energy contribution from the solar panels might be minimal in comparison to the vehicle’s overall energy needs.

What do you expect the role of VIPV to be like in the mid-term/long-term within mobility? What do you see as possible adoption scenarios?

In the mid-term, VIPV could play a role in specific niche applications that exist on the fringes of the mobility sector, where the benefits of VIPV can be maximized. For instance, cooling trucks or city buses are prime candidates for VIPV integration. These vehicles have large surface areas that can accommodate solar panels and they have relatively high energy needs for auxiliary systems like refrigeration or air conditioning that can be supplied by VIPV.

On the other side of the mobility spectrum, we have lightweight vehicles where VIPV could play a role. We could classify these vehicles as urban mobility solutions. These vehicles, such as tuktuks or small city cars, have a lower energy usage causing VIPV to be able to generate a larger share.

Looking further ahead, the role of VIPV depends on whether we will be successful to make fundamental changes in the transportation system. For VIPV to have a bigger impact, there needs to be a shift to more efficient vehicle design. This means rethinking how vehicles are constructed, focusing on aerodynamic designs and overall energy efficiency. In that sense, VIPV could help push this development.

What do you think is the effect of VIPV on infrastructure (electricity in general and charging infrastructure more specifically)?

In theory, VIPV could help reduce overall electricity demand on the grid. By generating their own electricity, vehicles with integrated solar panels would require less frequent charging from the grid.

However, this effect depends on the share of VIPV in the total vehicle number. Since I do not expect a significant uptake of VIPV, this effect will be limited. The effect of electric vehicles in general on the electricity grid through bi-directional charging will be significantly larger if those “mobile batteries” will be integrated into the electricity grid design and consumption /production patterns

N2.3 Interview with IM Efficiency

IM Efficiency is a company specializing in Solar on Top solutions: a solar panel that can be integrated onto the roofs of vehicles, such as trailers. The interviewee is a representative of the company.

What do you think is the added value of VIPV?

IM Efficiency mainly focuses on integrating solar panels on commercial vehicles, such as trailers. IM Efficiency’s Solar on Top consists of three components: (1) the PV panels, (2) the battery and (3) the truck’s energy management system (which contains IM Efficiency’s IP). For this type of vehicle, the added value lies in reducing CO_2 emissions from transport, saving fuel, and increasing trailer reliability. The Solar on Top solution uses solar energy to power electrical devices – primarily in the trailer and, if there’s surplus energy, in the truck – leading to less diesel dependency and more sustainable transport. Currently, over 100 trailers equipped with Solar on Top are operating in the EU, about 10 of which are equipped with a solar sensor for the SolarMoves project.

In your opinion, what are the main benefits of integrating PV into vehicles?

As mentioned earlier, IM Efficiency focuses on commercial vehicles. For these vehicles, we see several benefits:

- **Cost savings**: Both diesel and electric trucks will need fewer refuelling or charging stops, reducing operational costs.
- **Emission reduction**: Diesel trucks will consume less fuel because some functions run on solar energy, reducing fuel use by about 4–9% and lowering emissions. For electric vehicles, solar ensures that consumed electricity comes from a renewable source. For example, solar can power the truck’s air conditioning when stationary, so the diesel engine doesn’t need to run. A key driver here is EU VECTO regulations requiring trailers to reduce emissions, and Solar on Top is one solution. Additionally, in Germany, tolls are based on CO_2 emission class (VECTO score), so trucks with Solar on Top can fall into a cheaper class.
- **Greater reliability**: Solar panels ensure trailers always have enough electricity for equipment like loading/unloading systems, essential for smooth logistics.
- **Extended range**: For electric vehicles, integrated solar panels can add up to 10% extra range – a significant advantage in transport.
- **Battery life extension**: The system prevents truck batteries from dropping below critical levels, extending their lifespan. At Action, this led to a threefold reduction in battery replacements.

Different companies emphasize these benefits differently.

What do you perceive as the potential drawbacks or challenges of the adoption of VIPV?

As IM Efficiency, we see no disadvantages regarding the adoption of VIPV in commercial vehicles. However, we do recognize several challenges that hinder VIPV adoption.

There is a relative lack of awareness of the product. Many truck owners and carriers are unfamiliar with VIPV and are also sceptical. Over the past six months, the economy has been under pressure, which is also felt in the logistics sector. Carriers face low profit margins and are therefore relatively risk-averse when it comes to investments like VIPV. The payback period estimated by IM Efficiency at five years may be perceived as too long.

A second challenge is the lack of consistent regulations across different European countries. For companies operating internationally, it is important that regulations are uniform so they do not face varying requirements and standards in each country. Consistent regulations help accelerate VIPV adoption and create a level playing field among all market participants.

Examples of competing (technical) developments for VIPV include the development of the electric axle and improvements in the aerodynamics of trucks and trailers.

What do you expect the role of VIPV to be like in the mid-term/long-term within mobility? What do you see as possible adoption scenario's?

This depends greatly on the type of vehicle. The European Union has set ambitious goals to reduce CO_2 emissions and accelerate the transition to sustainable energy. For the transport sector, this means stricter emission standards will be introduced. From 2027, for example, trailers will need to comply with new emission norms that require them to reduce their emissions. This could force transport companies to invest in technologies such as VIPV.

Within commercial vehicles, integrating solar panels on trailers is the most valuable. This is because trailers offer a large surface area for installing solar panels, which leads to higher energy generation. Moreover, for trailers, it is a technically relatively simple solution, as the flat surface makes integration easier compared to passenger vehicles.

Therefore, we foresee that by 2030 a large share of trailers will have solar panels on their roofs – around 50%. In the long term (2050), adoption will be widespread, and we expect that almost all trailers will have solar panels. At that point, VIPV on trailers will have become the standard.

For passenger cars, the situation is different. From my perspective, VIPV adoption for this type of vehicle will likely not take off or only minimally. This is because passenger cars are less suitable for solar panel integration due to their smaller surface area and other technical constraints, such as the importance of aerodynamic design. Therefore, VIPV adoption will mainly occur in commercial transport, where the solar yield is greatest.

What do you think is the effect of VIPV on infrastructure (electricity in general and charging infrastructure more specifically)?

With Solar on Top, real solar energy is generated at the point where it is consumed. By producing solar energy on-site, trailers can reduce pressure on the infrastructure. This means less external energy is needed, which can lead to fewer investments in charging stations and more efficient use of the electricity grid. If trailers are self-sufficient in their energy needs, dependence on external energy sources decreases, improving the overall efficiency of the transport network.

N2.4 Interview with TNO

The interviewee is a researcher at TNO with experience in solar energy, focusing on areas such as system integration and solar energy on vehicles.

What do you think is the added value of VIPV?

Solar panels on vehicles can help with the electrification of transport needed to meet climate targets, especially because the electricity grid in the Netherlands does not have sufficient capacity to supply the growing electric fleet with power.

In your opinion, what are the main benefits of integrating PV into vehicles?

VIPV ensures that you need less power from the grid, throughout the whole year. Therefore, VIPV can, in the short term, help with the electrification of transport, mainly because grid congestion is increasing and the grid capacity is insufficient to supply the growing number of electric vehicles.

This also results in more flexibility in charging behaviour, affecting the distribution of charging times among users. Consequently, the demand for grid capacity for charging of electric vehicles will decrease.

It also leads to extra convenience. For example, passenger vehicles used for short distances would hardly need to be charged in summer.

For heavy transport, it can also contribute to achieving CO_2 emission reduction targets set by the EU for this group of vehicles. Emission reduction can prevent fines, making investments in VIPV potentially attractive.

Additionally, the development of VIPV systems can stimulate innovation and lead to new technological breakthroughs in solar energy. This way, we ensure we are not betting on just one horse.

What do you perceive as the potential drawbacks or challenges of the adoption of VIPV?

For passenger vehicles, one of the biggest obstacles is the aesthetic integration of solar panels. It is relatively difficult to integrate solar panels in a way that is both functional and visually appealing without compromising the vehicle's design. Moreover, most current technologies are glass-based, which is prohibited for hoods due to safety reasons.

This adds extra complexity, as alternative materials must be found that are both safe and effective. Replacing glass with plastics such as polycarbonate also brings challenges, such as scratch resistance.

Because the surface area of vehicles, especially passenger cars, is limited, it is important that the solar panels have high efficiency. A possible alternative to the current modules, mostly based on crystalline silicon, is a module based on a tandem solar cell. However, these contain lead, and its use is prohibited in vehicles under the End of Life Vehicle Directive.

Next to that, the yield of the solar panels depends on location and weather conditions. For example, in warm climates where vehicles are often parked in the shade, the effectiveness of the panels can decrease.

Another challenge for VIPV adoption is that initial investments are still high. This makes subsidies necessary to get the technology off the ground. In addition, the current charging infrastructure is not optimally aligned with VIPV use. There is little incentive for users to charge at specific times, and public charging stations often have constant rates throughout the day, which does not encourage off-peak charging. This means VIPV owners are not rewarded for their flexible charging behaviour.

What do you expect the role of VIPV to be like in the mid-term/long-term within mobility? What do you see as possible adoption scenarios?

In the short- to mid-term (i.e. now to 5–15 years), solar panels can help accelerate the electrification of transport, mainly to bypass the limited capacity of the electricity grid.

However, the interviewee doubts whether it will be a cost-effective solution in the long term.

What do you think is the effect of VIPV on infrastructure (electricity in general and charging infrastructure more specifically)?

VIPV can help reduce the total demand for electricity from the grid by generating solar energy directly on vehicles. It can also contribute to flexibility in charging behaviour. People have more opportunity to postpone their charging moment. Depending on location and weather, this will result in a different distribution.

As mentioned earlier, the current charging infrastructure is not optimally aligned with VIPV use. There is little incentive for users to charge at specific times, and public charging stations often have constant rates throughout the day, which does not encourage off-peak charging.

By reducing electricity demand, VIPV can partially postpone the investments needed in the electricity grid reinforcement to supply the growing electric fleet. This is especially relevant in areas where grid congestion occurs. However, it will only help delay these investments. Ultimately, they will still be necessary to meet climate targets.

N2.4 Interview with DG MOVE

The interviewee is a representative of DG MOVE working on sustainable mobility.

What are the main goals with regards to mobility for the European Union? To what extent do you think VIPV could contribute to these goals?

The main goal is to support the decarbonisation of transport, aiming for zero-emission vehicles by 2035 (for newly purchased vehicles). VIPV can play a role in this from two perspectives. On the one hand, VIPV can improve overall energy efficiency of the vehicle, and take away barriers such as range limitations that hamper EV adoption. On the other hand, VIPV can enhance the interaction with infrastructure by supporting vehicle-to-grid capabilities. This means that vehicles can not only extract electricity from the grid, but also supply electricity e.g. through integration with homes.

Have there been any changes recently with regards to the goals or perspective on VIPV?

Regardless of the new political configuration in the European Parliament as a result of the European elections in 2024, the interviewee expects the overall policy vision to remain stable and supportive of technologies like VIPV. The focus lies on maintaining European competitiveness whilst promoting innovative sustainable technologies (e.g., link to Draghi report). The interviewee believes that the political appetite for supporting sustainable transport solutions like VIPV will remain strong.

Are there any current policies that would stimulate or hinder the adoption of VIPV?

There are no specific policies exclusively aimed at the adoption of VIPV specifically. However, there are strategic roadmaps and pilot projects that provide indirect support. For example, the Automotive Action Plan and renewable energy strategies include language that supports smart charging and the integration of solar PV technology. Additionally, research funding and pilot projects have been used to explore and experiment with VIPV technology. These policies and initiatives create an ecosystem that supports the adoption of VIPV by addressing technological and infrastructure challenges.

Do you see the added value of VIPV?

The interviewee sees the following added values of VIPV:

1. Extended vehicle range: VIPV can generate additional electricity which can help extend the range of EVs, reducing the need for recharging.
2. Improved efficiency: integration of VIPV on vehicles can lead to manufacturers improving energy efficiency of the vehicle and potentially reduce battery size.
3. Integration with infrastructure: VIPV can provide additional grid services as compared to a conventional vehicle as the vehicle can now also generate electricity and supply this to the grid.
4. Support for decarbonisation goals: VIPV can support in emission reduction related to mobility and thus aligns with the EU's goal of decarbonizing all newly sold vehicles by 2035.

What should the role of policy be in the adoption of VIPV?

Ideally, the market should drive the adoption of VIPV without the need for new policies. However, adjustments to existing policies, such as type approval, may be necessary in the future. If there exist technological or economic challenges or gaps, policy can encourage and fund research to address these challenges and improve the overall effectiveness of the technology.

Do you see a difference between the private consumers and commercial consumers (e.g. trucks and buses)?

Through research funded by the EU like this project, we aim to obtain a better understanding of VIPV: how do the cost and benefits relate to each other for both passenger vehicles and commercial vehicles. For passenger vehicles, VIPV could impact the energy efficiency. However, there are underlying challenges, such as integration with the vehicle's architecture and safety concerns.

For commercial vehicles, theoretically, VIPV could make a lot of sense due to the large surface areas these vehicles have available for the installation of PV, leading to greater energy generation. VIPV could be especially beneficial in regions with high sun exposure. For example, buses operating in countries as Spain, Italy and Portugal could benefit significantly from VIPV. We are aware that these buses have substantial energy consumption for secondary utilities like air conditioning (~15% of total energy consumption), which could be (partly) covered through VIPV. However, we do not really see commercial vehicles with PV on the roads yet and we are curious to understand what are the reasons of this.

N3 Assessment of quantitative costs and benefits

This appendix explains how factors – TCO, CO_2 emissions, revenues, and convenience – were quantified for the Value Case Methodology. For each factor, the underlying calculation approach, assumptions, and scope are described.

Factor: [TCO (CAPEX, OPEX)]

Relevant stakeholders: [Vehicle owners (LPXX, LVXX, HBXX, HTXX]
Desired change: ↓

The Total Cost of Ownership (TCO) for vehicles with and without VIPV was quantified in task 1 of this project. In the Cost & Benefit model, the TCO is displayed as the difference between a vehicle with VIPV and without VIPV

The TCO consists of all costs during the use period of five years. It is the summation of the Capital Expenditures (CAPEX) and Operating Expenditures (OPEX). CAPEX is calculated by subtracting the residual value from the purchase cost. Discounting is applied to costs made after the purchase moment, using 8% for companies and 2.25% for private owners. The OPEX consists of energy costs, maintenance costs, taxes and insurance costs.

In task 3, an additional comparison was performed that was not included in task 1: ICE truck (HTXX) with and without VIPV. To calculate the TCO for this case, the only parameter that changes are the costs related to energy consumption. The VIPV yield is translated into a reduction in diesel use, resulting in lower operational costs. All other cost components remain unchanged. This approach allows to compare the cost reduction from lower diesel consumption with the additional capital costs associated with the purchase of VIPV.

Factor: [CO_2 emissions]

Relevant stakeholders: [Vehicle owners (LPXX, LVXX, HBXX, HTXX), Policy maker]
Desired change: ↓

Emission reductions over a period of five years[66] are calculated in Task 1 of the project, based on reduced external electricity demand achieved through VIPV. For all vehicle archetypes, EVs equipped with VIPV are compared to those without VIPV. The external electricity savings as a result of VIPV are converted into avoided emissions by multiplying them with the emission factor of the European electricity grid (in g CO_2-eq/kWh).

For truck-archetypes (HTXX), a second comparison is made: ICE trucks equipped with VIPV are compared to ICE trucks without VIPV. In these instances, the energy savings generated by VIPV are converted into a reduction in diesel consumption, taking into account efficiency losses. This reduction in diesel use is then multiplied by the diesel emission factor to determine the overall emission savings for diesel trucks.

In the cost-benefit model, the emission reduction is calculated both at the level of individual vehicle archetype and at the fleet level. The latter reflects the total potential impact of VIPV adoption across the European vehicle fleet. This fleet-level perspective is especially relevant for policy

[66] Emission reduction for vehicle archetypes are calculated over a five-year period, consistent with the timeframe applied to calculate the TCO. However, the emission reduction on the fleet level are calculated per year.

makers. For this stakeholder, the annual CO_2 emission reduction are calculated and compared to the total road emission of the EU in 2022.

Factor: [Revenues]

Relevant stakeholders: [CPO, Energy Company, OEM/Car manufacturer, Solar Solution Manufacturer]
Desired change: ↑

The effect of VIPV on revenues of stakeholders in different scenarios is quantified. For stakeholders related to electricity from the grid (CPO and energy companies), the adoption of VIPV results in a reduction of revenues due to lower electricity consumption from the grid by electric vehicles. However, for OEM/Car and Solar Solution Manufacturers, the adoption of VIPV can lead to an increase in revenues through higher sales of VIPV-equipped vehicles and associated components. For each stakeholder, a different approach is applied to calculate the effect of VIPV on their revenues.

CPO and Energy Company

In task 1, the average potential reduction of consumption from the electricity grid as a result of VIPV is calculated per archetype. To determine the loss of revenues for the CPO, the reduced grid consumption is multiplied with the share of street and fast charging with their respective rates for the share of the fleet which has adopted VIPV. This gives an indication of the potential loss in revenues for the CPO as a result of VIPV.

The same approach is followed for the stakeholder *Energy Company* using the share and rate of the electricity consumption at home.

OEM/Car Manufacturer and Solar Solution Manufacturer

The increase in revenues for the OEM/Car Manufacturer was quantified by multiplying the cost of the VIPV technology per vehicle with the projected annual sales of VIPV-equipped vehicles in 2030 per scenario. This represents the additional turnover generated from the sale of vehicles integrated with VIPV.

For the Solar Solution Manufacturer, revenues were derived from the same number of VIPV units sold to OEMs, multiplied by the OEM markup that reflects the price increase applied by the OEM when purchasing the VIPV technology.

Factor: [Convenience]

Relevant stakeholders: [Vehicle owners (LPXX, LVXX, HBXX, HTXX]
Desired change: ↑

The convenience score reflects the reduction (%) in the number of charging moments enabled by VIPV technology, as quantified in Task 1 of the project, assuming charging strategy 3. By generating electricity that can be stored in the vehicle, VIPV reduced the need for frequent charging. The amount of reduction can be quite extreme: almost no charging in the summer time for a small passenger car in an urban environment with very limited use. However, in most cases, the reduction in charging per year is more limited on the scale of 10%-15% on an annual basis with a high dependence on summer.

N4 Assessment of qualitative costs and benefits

This appendix explains how qualitative costs and benefits were assessed. For several costs and benefits, especially those with a more behavioural nature, no reliable, consistent publicly available quantification methodology currently exists. For these factors, a qualitative assessment was applied based on expert opinion of the consortium and modelling outputs of tasks 1. The assessment uses a scoring scale from 0 to 2, where 0 represents limited or negligible benefit, 1 a moderate benefit and 2 a high benefit. This appendix describes the rationale behind each score.

Factor: [Parking location independency]

Relevant stakeholders: [Vehicle owners (LPXX, LVXX, HBXX, HTXX]
Desired change: ↑

The scoring of the factor *Parking location independency* is determined based on the parking flexibility and the reduction in charging moments (see factor *Convenience*).

A score of 1 or higher is only assigned to vehicle archetypes that have inherently high parking flexibility. For vehicles with fixed depot or home charging (e.g. buses, regional trucks), the benefit is assumed to be zero, regardless of the charging moment reduction.

For vehicles with high parking flexibility, the charging moment reduction determines the final score:

Table 91: Rationale for qualitative scoring (0-2) of factor Parking location independency

Factor: [Parking location independency]		**Relevant stakeholders: [Vehicle owners (LPXX, LVXX, HBXX, HTXX]**
Score	Charging frequency (%)	Explanation
0	0% to –15%	The reduction in charging frequency is too small to alter user behaviour or reliance on charging infrastructure. No meaningful increase in parking flexibility.
1	–15% to –30%	The user may skip ~1 in 5 charging sessions. This provides some behavioural benefit and occasional freedom from charging constraints.
2	–30% to –53%	Significant decrease in charging frequency. Users gain substantial independence from needing charging points at specific locations, especially valuable in urban contexts.

Factor: [Autonomy]

Relevant stakeholders: [Vehicle owners (LPXX, LVXX, HBXX, HTXX]
Desired change: ↑

Rationale

The factor autonomy reflects how independent a vehicle can become from the grid as a result of VIPV. This is primarily driven by two factors:

- Energy demand (related to trip distance): Vehicles with low daily energy needs (e.g. short urban trips or occasional use) benefit more, as VIPV can cover a relatively larger share of their consumption. For long-distance or intensive use vehicles, VIPV contributes less proportionally, so autonomy gains are limited.
- Reduction in charging moments: A higher percentage reduction in charging frequency suggests that the vehicle relies less on external infrastructure, increasing its grid-independence. This is especially valuable where access to charging is limited or in the event of grid outages.

Together, these factors determine whether VIPV meaningfully increases a vehicle's self-sufficiency, which is the basis for the autonomy score.

Table 92: Rationale for qualitative scoring (0-2) of factor Autonomy

Factor: [Autonomy]		**Relevant stakeholder: Relevant stakeholders: [Vehicle owners (LPXX, LVXX, HBXX, HTXX]**
Score	Charging frequency (%)	Explanation
0	0% to –10%	Vehicle archetypes with very high daily or trip energy demand, such as heavy-duty trucks and buses or vehicles that have daily long-distance trips, are assigned a score of 0. In these cases, VIPV can only provide a negligible share of total energy needs, resulting in minimal reduction in charging frequency and negligible improvements in autonomy.
1	–10% to –30%	A score of 1 is assigned to vehicle archetypes that achieve a moderate reduction in charging events. These typically have lower energy demand than heavy-duty vehicles, but still require substantial charging, limiting VIPV's relative contribution.
2	–30% to –53%	Archetypes characterised by both a substantial decrease in charging events and low daily energy demand receive a score of two, since VIPV can satisfy a larger share of their total energy needs.

Factor: [Eco-friendly image]

Relevant stakeholders: [Vehicle owners (LPXX, LVXX, HBXX, HTXX]
Desired change: ↑

Rationale

A high score of 2 is attributed to all vehicle archetypes for this factor in the earlier years (2023, 2025, and 2030), while a lower score of 1 is allocated across all archetypes in the *Ultimate* case. Between 2023 and 2030, VIPV technology remains relatively new with limited market penetration. Consequently, VIPV is considered a differentiator and leads to a distinct eco-friendly image. As it is assumed that adoption of VIPV becomes more widespread in the *Ultimate* case, it does not offer a unique advantage anymore, resulting in a lower score (1).

Table 93: Rationale for qualitative scoring (0-2) of factor Eco-friendly image

Factor: [Eco-friendly image]	**Relevant stakeholders: [Vehicle owners (LPXX, LVXX, HBXX, HTXX]**
Score	Explanation
0	This score is not assigned for the factor *Eco-friendly image* of the vehicle, as it is assumed that in any case, VIPV brings added value to the user in terms of its sustainable image.
1	A score of 1 is assigned to all vehicle archetypes in the *Ultimate* case, as it assumed that VIPV will not be a differentiator due to its more widespread adoption. Hence, a lower score is assigned then in earlier years.
2	All vehicle archetypes receive a score of 2 from the base year (2023) to 2030. VIPV is anticipated to add substantial value by enhancing the eco-friendly image of vehicles; as an emerging technology with limited adoption, it serves as a significant differentiator in the market.

Factor: [Range]

Relevant stakeholders: [Vehicle owners (LPXX, LVXX, HBXX, HTXX]
Desired change: ↑

Rationale

A score of 0 is attributed to all vehicle archetypes for this factor, as indicated by the outcomes of task 1. The analysis revealed that range extension provided by VIPV is limited and does not deliver a substantial benefit. The range of a vehicle is especially relevant for long-distance trips, often with high speeds and ultimately high energy consumption. As VIPV has a low peak power, the output is small, making it insufficient to have a significant impact on range extension during high-speed trips, where energy consumption is higher. Therefore, VIPV only have minimal effect on driving range, leading to a score of 0 across all vehicle archetypes.

Table 94: Rationale for qualitative scoring (0-2) of factor Range

Factor: [Range]	**Relevant stakeholders: [Vehicle owners (LPXX, LVXX, HBXX, HTXX]**
Score	Explanation
0	A score of 0 is assigned to all vehicle archetypes and results from task 1 indicate that VIPV has little to no effect on range extension.
1	This score is not assigned to any vehicle archetype for the factor *Range*, as the contribution of VIPV on range extension is too limited to bring substantial added value.
2	This score is not assigned to any vehicle archetype for the factor *Range*, as the contribution of VIPV on range extension is too limited to bring substantial added value.

Factor: [Battery Lifetime]

Relevant stakeholders: [Car / OEM manufacturer]

Desired change: ↑

Rationale

A score of 0 or 2 is assigned for the factor *battery lifetime improvement*. Improvements in battery lifetime can occur when VIPV enables more gradual and stable charging patterns, reducing battery stress and degradation. However, this benefit is conditional on the implementation of an advanced Battery Management System (BMS) capable of optimising charging behaviour based on VIPV input. As such systems are not yet widely available, a score of 0 is assigned for the short term (2025–2030). A score of 2 is assigned in the longer term (for the *Ultimate* case), when BMS integration is expected to become standard, allowing VIPV to actively contribute to battery lifetime improvement.

Table 95: Rationale for qualitative scoring (0-2) of factor Battery Lifetime

Factor: [Battery Lifetime]	**Relevant stakeholders: [Vehicle owners (LPXX, LVXX, HBXX, HTXX]**
Score	Explanation
0	A score of 0 is assigned to all archetypes in the short term (until 2030), as it is assumed no advanced Battery Management System (BMS) is implemented (yet). Without this advanced BMS, VIPV is not able to influence charging patterns or mitigate battery degradation.
1	A score of 1 is not applied, as improvements in battery lifetime are expected to be either not present (0) or fully realised once advanced BMS is implemented (2).
2	A score of 2 is assigned when it is assumed that the advanced BMS is fully implemented. This is assumed to occur in the Ultimate case.

Factor: [Regulatory Compliance]

Relevant stakeholders: [Car / OEM manufacturer]
Desired change: ↑

Regulatory compliance is not considered a relevant driver for VIPV adoption among commercial vehicle owners, as current EU CO_2 emission regulations apply at the manufacturer level (OEMs), not to fleet operators. Instead, pressure on commercial fleet owners primarily stems from indirect channels such as low-emission zones, public procurement criteria, and voluntary corporate sustainability commitments. These mechanisms may influence vehicle selection, particularly in emission-sensitive operations.

Vehicle and OEM manufacturers do face binding targets and fines under regulations like (EU) 2019/1242 and (EU) 2019/631. However, VIPV does not provide any recognised reduction in emissions compared to EVs, which already have zero tailpipe emissions. As a result, VIPV does not contribute to compliance of regulatory targets, so a score of zero is applied across all scenarios – except in the *High Uptake Plus* scenario, where VIPV is assumed to accelerate EV adoption and thereby reduce penalty exposure for manufacturers. In this case, a score of 2 is assigned.

Table 96: Rationale for qualitative scoring (0-2) of factor Regulatory Compliance

Factor: [Regulatory Compliance]	**Relevant Stakeholders: [Car / OEM manufacturer]**
Score	Explanation
0	A score of 0 is assigned for this factor as current regulations do not assign any added value to vehicles with VIPV compared to electric vehicles without it.
1	This score is not assigned, as current regulations do no assign added value to electric vehicles with VIPV compared to electric vehicles without it.
2	A score of 2 is assigned in the *High Uptake Plus* scenario where VIPV is assumed to accelerate the adoption of EVs, thereby reducing penalty exposure for manufacturers.

Factor: [Brand Image]

Relevant stakeholders: [OEM and/or car manufacturer]

Desired change: ↑

Brand value is a strategic consideration for car manufacturers, particularly in the context of sustainability leadership, innovation positioning, and ESG performance. However, due to its intangible nature and lack of clear quantification methods, this factor was also assessed qualitatively.

The assessment evaluates how VIPV adoption can enhance brand image in different timeframes, applying a score ranging from 0 to 2. The score depends on the level of VIPV uptake in a given scenario. If there is no VIPV uptake, the score remains low (0), as the brand is not offering VIPV. When VIPV adoption occurs at a level sufficient to set the brand apart from its competitors, a high (2) score is assigned. In this case, VIPV is regarded as an innovative technology that signals sustainability and forward-thinking. As VIPV becomes more common across the market, the score is adjusted to a medium level (1), since differentiation between brands diminishes once VIPV is widely adopted. Over time, in scenarios where the technology becomes more widespread and its novelty fades, a lower score will be assigned, reflecting the reduced distinctiveness associated with VIPV adoption. This counts for the *Ultimate* timeframe.

Table 97: Rationale for qualitative scoring (0-2) of factor Brand Image

Factor: [Brand Image]	**Relevant Stakeholders: [Car Manufacturer]**
Score	Explanation
0	This score is assigned in the base scenario in each year as no VIPV uptake is assumed so there is no added value to the car manufacturer in terms of brand image.
1	A medium score (1) is assigned in cases where VIPV adoption is too widespread for the car manufacturer to differentiate itself from other car manufacturers through offering this technology.
2	A high score (2) is assigned when adoption of VIPV occurs at a level sufficient enough to set the brand apart from its competitors.

Factor: [Grid Utilisation]

Relevant stakeholders: [Grid Operator]

Desired change: ↓

VIPV can reduce peak charging demand and thereby alleviate local grid congestion. However, it does not eliminate congestion risks altogether. The added value of VIPV is particularly relevant in the short term and under high adoption scenarios, especially where smart charging is not yet fully implemented. Over time, as smart charging becomes more widespread and effective, the marginal contribution of VIPV decreases. In the *Ultimate* case, it is assumed that smart charging will be largely implemented across the system, leading to a lower but not necessarily zero benefit from VIPV, as local variation and implementation gaps of smart charging may continue to exist. As a result, higher scores are assigned in near-term timeframes and high-adoption scenarios, while lower scores are used for the *Ultimate* case to reflect a reduced added value.

In the High Uptake Plus scenario, where VIPV accelerates EV adoption, the net effect on grid utilisation may become ambiguous. While VIPV reduces the peak charging load of each vehicle, a larger EV fleet increases total electricity demand. This can reduce or even offset the overall benefit of VIPV in relieving grid congestion. Therefore, in the *High Uptake Plus*, a lower score is assigned for this factor.

Table 98: Rationale for qualitative scoring (0-2) of factor Grid Utilisation

Factor: [Grid Utilisation]	**Relevant Stakeholders: [Grid Operator]**
Score	Explanation
0	A low score (0) is assigned when VIPV adoption is too low to meaningfully impact infrastructure planning. This applies to 2023 and 2025 scenarios across all cases, as well as every year in the base case scenario, where no VIPV uptake is assumed. A score of 0 is also given to *Ultimate* cases with low VIPV adoption, as the widespread implementation of smart charging is expected to limit the added value of VIPV. In the *High Uptake Plus* scenario for the *Ultimate* case, benefits from VIPV are offset by the higher EV adoption rate, resulting in no net improvement in grid utilisation.
1	A medium score (1) is assigned to 2030 scenarios with moderate VIPV adoption. In these cases, the limited rollout of smart charging allows VIPV to provide some added value in reducing grid strain. This score is also applied to the *High Uptake Plus* scenario for the *Ultimate* case, where smart charging adoption limits the additional benefit of VIPV.
2	A high score (2) is assigned in the High Uptake scenario for 2030, where VIPV significantly alleviates grid congestion. The lack of widespread smart charging in this period enhances the relative benefit of VIPV.

Factor: [Investments in Infrastructure]

Relevant stakeholders: [Grid Operator, Charging Point Operator]
Desired change: ↓

Rationale

VIPV reduces the electricity consumption of electric vehicles from external sources, namely the electricity grid (operated by Grid Operators) and the charging infrastructure (operated by Charging Point Operators). The effect of VIPV on the need for infrastructure investments differs for each.

Grid infrastructure

Due to a reduced peak electricity demand, VIPV can help defer or reduce infrastructure investments, particularly at the local grid level. As mentioned previously, VIPV increases charging flexibility as part of the electricity demand is provided by VIPV, therefore the timing of charging moments can shift, leading to a different temporal distribution in charging behaviour compared to a situation without VIPV. As a result of this, peak electricity demand can be lower and hence, also the needed infrastructure capacity.

However, this different temporal distribution in charging behaviour and accompanying reduced peak demand could also be achieved by the implementation of smart charging. Hence, when smart charging would be fully implemented, the additional impact of VIPV becomes minimal.

As such, the benefit depends strongly on the degree of smart charging implementation as well as VIPV adoption rates. In 2030, when smart charging is assumed to be only partially implemented, flexibility in charging moments can be increased through VIPV resulting in a more distributed charging behaviour. This results in a lower peak electricity demand and can therefore also defer infrastructure investments.

Table 99: Rationale for qualitative scoring (0-2) of factor Investments in infrastructure (Grid Operator)

Factor: [Investments in infrastructure]	**Relevant Stakeholders: [Grid Operator]**
Score	Explanation
0	A low (0) score is assigned in at timeframes in scenarios when adoption of VIPV is low, hence the impact of VIPV on electricity peak demand is too marginal to influence infrastructure planning.
1	A medium (1) score is assigned where VIPV has a moderate positive effect on peak electricity demand. This occurs in scenarios with sufficient VIPV adoption where either 1) smart charging is already widely implemented (assumed in the *Ultimate* case), thereby limiting the additional impact of VIPV, or 2) VIPV accelerates EV uptake (as in the *High Uptake Plus* scenario), partially offsetting its benefits through higher overall electricity demand.
2	A high (2) score is assigned when VIPV provides a relatively substantial contribution to lowering peak electricity demand. This occurs in timeframes with sufficiently high VIPV adoption when smart charging is not yet widely adopted. As a result, VIPV has a stronger effect on reducing peak electricity demand.

In contrast, in the *Ultimate* case, where it is assumed that widespread smart charging is in place, the added value of VIPV becomes lower as smart charging has a stronger effect on optimal grid utilisation.

In the *High Uptake Plus* scenario, where VIPV accelerates EV adoption, the overall electricity demand of the vehicle fleet increases, offsetting the benefits of reduced per-vehicle peak demand. In this context, the larger EV fleet could even increase the need for infrastructure investments.

Charging infrastructure

VIPV could also influence the need for charging infrastructure reinforcements, but this impact is limited due to its seasonal variation. In winter, when solar yield is low, VIPV has little effect on the frequency of charging, meaning that the overall number of charging points required remains largely unchanged. However, in summer, VIPV can results in a reduction in charging moments. As a result, in regions with high visitor numbers in summer, VIPV could significantly reduce charging needs during peak travel seasons. In these summer hotspots, VIPV could therefore help lower required charging station capacity.

However, since the cost–benefit model is not geographically differentiated, this benefit is considered limited at the system level, and a low score is therefore applied across all cases.

Table 100: Rationale for qualitative scoring (0-2) of factor Investments in infrastructure (CPO)

Factor: [Investments in infrastructure]	**Relevant Stakeholders: [Charging Grid Operator]**
Score	Explanation
0	A low (0) score is assigned across all scenarios, as the cost benefit model is not geographically specified and the potential benefit of VIPV in reducing charging infrastructure capacity is only relevant in limited, location-specific cases (e.g. summer tourist hotspots). Due to the seasonal variability of solar yield and the minimal effect of VIPV on charging frequency during winter months, the impact on overall needed charging points is limited.
1	Not applied.
2	Not applied.

Factor: [Comfort (i.e. noise reduction)]

Relevant stakeholders: [Vehicle Owner (HTXX)]
Desired change: ↑

Rationale

The comfort (primarily noise reduction) is only relevant when comparing diesel trucks with and without VIPV, not in the case of electric trucks. In diesel trucks, auxiliary systems such as cabin climate control or refrigeration require engine idling, which results in considerable noise and local air pollution. When a diesel truck is equipped with VIPV, the solar installation can be connected to the auxiliary battery which provide electricity for these services, thereby reducing the need for idling. Benefits related to this are especially present when the driver is resting overnight in the vehicle. A high score (2) is provided when the archetype includes overnight rests and a moderate score (1) is assigned when the archetype does not include overnight rests, but shorter breaks are taken in the vehicle.

In contrast, electric vehicles already power these systems from their main battery, so VIPV does not provide additional comfort or noise-reduction advantages in this case. As a result, no added value is assigned to VIPV for comfort when comparing it to EVs.

Table 101: Rationale for qualitative scoring (0-2) of factor Comfort (i.e. noise reduction)

Factor: [Comfort (i.e. noise reduction)]	**Relevant Stakeholders: [Vehicle Owner (HTXX)]**
Score	Explanation
0	This score is assigned to archetypes with a use pattern when there is no overnight use or rest in the vehicle, as VIPV then provides negligible benefits in terms of noise reduction.
1	A medium (1) score is assigned when the archetype involves only shorter breaks in the vehicle (not overnight stays). VIPV can reduce engine idling for auxiliary services during these brief periods.
2	VIPV delivers a high comfort benefit (score of 2) when the archetype includes overnight rests in the vehicle. This is because VIPV can significantly reduce engine idling for auxiliary services such as climate control or refrigeration overnight, reducing noise while the driver is resting.

N5 Valuation of costs and benefits for each timeframe

This appendix presents the valuation of costs and benefits per stakeholder across four timeframes: 2023 (base case), 2025, 2030 and Ultimate. For more information on scenarios and timeframes, see paragraph 3.3.2 and 3.4.3. For each timeframe, all relevant costs and benefits are valued, applying the methodology as described in Chapter 3.

A point to note is that energy consumption was not modelled for the *Ultimate* timeframe in Task 1. As a result, CO_2 emission reduction and revenue effects linked to changes in electricity consumption from the grid (e.g. for energy companies and CPOs) are not included for the Ultimate timeframe. This is shown in the form of a dash (-).

N5.1 Vehicle owners of passenger vehicles (LPXX)

This paragraph presents the valuation of costs and benefits for vehicle owners of passenger vehicles (LPXX).

Table 102: Vehicle owners of passenger vehicles (LPXX): Valuation of costs and benefits between EV and VIPV in ***2023***

		Delta EV &VIPV 2023										
		LP10	LP11	LP12	LP13	LP14	LP21	LP22	LP23	LP31	LP32	LP33
		Small passenger car				*Medium sized passenger car*				*SUV*		
Factor	**Desired change**	*Occasional use*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*	*Car sharing*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*
TCO [€ / 5 y]	↓	460	450	433	218	458	622	618	436	474	345	-90
Payback period [y]	↓	>5	>5	>5	>5	>5	>5	>5	>5	>5	>5	4.7
CO_2 emission [%]	↓	-41%	-46%	-28%	-14%	-13%	-40%	-25%	-13%	-52%	-33%	-17%
Autonomy	↑	2	2	2	0	0	2	2	0	2	2	1
Convenience	↑	31%	42%	22%	9%	5%	35%	24%	5%	50%	30%	13%
Range	↑	0	0	0	0	0	0	0	0	0	0	0
Battery lifetime	↑	0	0	0	0	0	0	0	0	0	0	0
Eco-friendly image	↑	2	2	2	2	2	2	2	2	2	2	2
Parking location independency	↑	2	2	2	1	2	2	1	1	2	1	1

Table 103: Vehicle owners of passenger vehicles (LPXX): Valuation of costs and benefits between EV and VIPV in ***2025***

		Delta EV &VIPV 2025										
		LP10	**LP11**	**LP12**	**LP13**	**LP14**	**LP21**	**LP22**	**LP23**	**LP31**	**LP32**	**LP33**
		Small passenger car				*Medium sized passenger car*				*SUV*		
Factor	**Desired change**	*Occasional use*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*	*Car sharing*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*
TCO [€ / 5 y]	↓	103	132	70	-163	81	126	117	-77	-7	-217	-696
Payback period [y]	↓	>5	>5	>5	4.0	>5	>5	>5	4.6	5.0	4.0	2.9
CO_2 emission [%]	↓	-45%	-46%	-30%	-15%	-14%	-44%	-27%	-14%	-53%	-36%	-18%
Autonomy	↑	2	2	2	1	0	2	2	1	2	2	0
Convenience	↑	35%	-36%	-27%	-10%	9%	-45%	-24%	11%	53%	35%	9%
Range	↑	0	0	0	0	0	0	0	0	0	0	0
Battery lifetime	↑	0	0	0	0	0	0	0	0	0	0	0
Eco-friendly image	↑	2	2	2	2	2	2	2	2	2	2	2
Parking location independency	↑	2	2	2	1	2	2	1	1	2	1	1

Table 104: Vehicle owners of passenger vehicles (LPXX): Valuation of costs and benefits between EV and VIPV in ***2030***

		Delta EV &VIPV 2030										
		LP10	**LP11**	**LP12**	**LP13**	**LP14**	**LP21**	**LP22**	**LP23**	**LP31**	**LP32**	**LP33**
		Small passenger car				*Medium sized passenger car*				*SUV*		
Factor	**Desired change**	*Occasional use*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*	*Car sharing*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*
TCO [€ / 5 y]	↓	-136	-64	-206	-480	-209	-144	-249	-464	-403	-676	-1,220
Payback period [y]	↓	3.7	4.3	3.3	2.4	3.4	3.9	3.4	2.7	2.9	2.3	1.7
CO_2 emission [%]	↓	50%	47%	35%	18%	-16%	-46%	-31%	-16%	-62%	-43%	-21%
Autonomy	↑	2	2	2	1	1	2	2	1	2	2	1
Convenience	↑	48%	43%	31%	11%	10%	47%	32%	12%	53%	41%	10%
Range	↑	0	0	0	0	0	0	0	0	0	0	0
Battery lifetime	↑	0	0	0	0	0	0	0	0	0	0	0
Eco-friendly image	↑	2	2	2	2	2	2	2	2	2	2	2
Parking location independency	↑	2	2	2	1	2	2	1	1	2	1	1

Table 105: Vehicle owners of passenger vehicles (LPXX): Valuation of costs and benefits between EV and VIPV in the ***Ultimate*** *timeframe*

Factor	Desired change	LP10	LP11	LP12	LP13	LP14	LP21	LP22	LP23	LP31	LP32	LP33
		Delta EV &VIPV Ultimate										
		Small passenger car				*Medium sized passenger car*				*SUV*		
		Occasional use	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*	*Car sharing*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*	*Daily urban commute*	*Daily peri-urban commute*	*Long-distance highway travel*
TCO [€ / 5 y]	↓	-129	-107	-271	-597	-292	-225	-353	-631	-388	-736	-1,423
Payback period [y]	↓	3.8	3.9	3.0	2.1	3.0	3.5	3.0	2.3	3.0	2.2	1.5
CO_2 emission [%][67]	↓	-	-	-	-	-	-	-	-	-	-	-
Autonomy	↑	2	2	2	1	1	2	2	1	2	2	1
Convenience	↑	-50%	-47%	-38%	-15%	-13%	-47%	-34%	-12%	-62%	-45%	-13%
Range	↑	0	0	0	0	0	0	0	0	0	0	0
Battery lifetime	↑	2	2	2	2	2	2	2	2	2	2	2
Eco-friendly image	↑	1	1	1	1	1	1	1	1	1	1	1
Parking location independency	↑	2	2	2	1	2	2	1	1	2	1	1

N5.2 Vehicle owner of vans (LVXX)

This paragraph presents the valuation of costs and benefits for vehicle owners of vans (LVXX).

Table 106: Vehicle owners of vans (LVXX): Valuation of costs and benefits between EV and VIPV in ***2023***

Factor	Desired change	LV11	LV12	LV21	LV22
		Delta EV vs. VIPV 2023			
		Small van		*Large van*	
		Local distribution	*Regional distribution*	*Local distribution*	*Regional distribution*
TCO [€ / 5 year]	↓	531	232	753	313
Payback period [years]	↓	>5	>5	>5	>5
CO_2 emission [%]	↓	-16%	-14%	-12%	-17%
Autonomy	↑	0	0	0	0
Convenience	↑	7%	7%	7%	2%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

[67] The energy consumption of vehicle archetypes was not calculated for the Ultimate scenario in Task 1. As a result, CO_2 emission reductions related to decreased energy consumption are not included for the Ultimate scenario.

Table 107: Vehicle owners of vans (LVXX): Valuation of costs and benefits between EV and VIPV in ***2025***

Factor	Desired change	Delta EV vs. VIPV 2025 LV11	LV12	LV21	LV22
		Small van		*Large van*	
		Local distribution	*Regional distribution*	*Local distribution*	*Regional distribution*
TCO [€ / 5 year]	↓	-82	-395	-100	-529
Payback period [years]	↓	4.6	3.6	4.6	3.6
CO_2 emission [%]	↓	-17%	-15%	-13%	-18%
Autonomy	↑	1	0	0	0
Convenience	↑	12%	10%	5%	4%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

Table 108: Vehicle owners of vans (LVXX): Valuation of costs and benefits between EV and VIPV in ***2030***

Factor	Desired change	Delta EV vs. VIPV 2030 LV11	LV12	LV21	LV22
		Small van		*Large van*	
		Local distribution	*Regional distribution*	*Local distribution*	*Regional distribution*
TCO [€ / 5 year]	↓	-554	-914	-732	-1210
Payback period [years]	↓	2.7	2.1	2.7	2.0
CO_2 emission [%]	↓	-21%	-18%	-16%	-22%
Autonomy	↑	1	0	0	0
Convenience	↑	14%	12%	7%	13%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

Table 109: Vehicle owners of vans (LVXX): Valuation of costs and benefits between EV and VIPV in the ***Ultimate*** *scenario*

Factor	Desired change	Delta EV vs. VIPV Ultimate LV11	LV12	LV21	LV22
		Small van		*Large van*	
		Local distribution	*Regional distribution*	*Local distribution*	*Regional distribution*
TCO [€ / 5 year]	↓	-709	-1,119	-947	-1,476
Payback period [years]	↓	2.4	1.8	2.4	1.8
CO_2 emission [%][68]	↓	-	-	-	-
Autonomy	↑	1	1	0	0
Convenience	↑	12%	17%	11%	13%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

N5.3 Vehicle owner of buses (HBXX)

This paragraph presents the valuation of costs and benefits for vehicle owners of buses (HBXX).

Table 110: Vehicle owners of buses (HBXX): Valuation of costs and benefits between ***EV*** *and* ***VIPV*** *in* ***2023***

Factor	Desired change	Delta EV vs. VIPV 2023 HB11	HB12	HB22	HB23
		Low-floor bus		*High-floor bus*	
		Urban public transport service	*Peri urban public transport service*	*Regional public transport*	*Long-distance highway travel*
TCO [€ / 5 y]	↓	674	769	407	-557
Payback period [Y]	↓	>5	>5	>5	4.2
CO_2 emission [%]	↓	-1%	-2%	-2%	-1%
Autonomy	↑	0	0	0	0
Convenience	↑	0%	1%	1%	0%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

[68] The energy consumption of vehicle archetypes was not calculated for the Ultimate scenario in Task 1. As a result, CO_2 emission reductions related to decreased energy consumption are not included for the Ultimate scenario.

*Table 111: Vehicle owners of buses (HBXX): Valuation of costs and benefits between **EV** and **VIPV** in **2025***

		Delta EV vs. VIPV 2025			
		HB11	HB12	HB22	HB23
		Low-floor bus		*High-floor bus*	
Factor	**Desired change**	Urban public transport service	*Peri urban public transport service*	*Regional public transport*	*Long-distance highway travel*
TCO [€ / 5 y]	↓	222	347	-11	-1,000
Payback period [Y]	↓	>5	>5	5.0	3.5
CO_2 emission [%]	↓	-1%	-2%	-2%	-1%
Autonomy	↑	0	0	0	0
Convenience	↑	0%	3%	0%	4%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

*Table 112: Vehicle owners of buses (HBXX): Valuation of costs and benefits between **EV** and **VIPV** in **2030***

		Delta EV vs. VIPV 2030			
		HB11	HB12	HB22	HB23
		Low-floor bus		*High-floor bus*	
Factor	**Desired change**	Urban public transport service	*Peri urban public transport service*	*Regional public transport*	*Long-distance highway travel*
TCO [€ / 5 y]	↓	-505	-315	-712	-1,855
Payback period [Y]	↓	4.0	4.3	3.6	2.6
CO_2 emission [%]	↓	-1%	-2%	-2%	-1%
Autonomy	↑	0	0	0	0
Convenience	↑	0%	0%	0%	0%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

*Table 113: Vehicle owners of buses (HBXX): Valuation of costs and benefits between **EV** and **VIPV** in the **Ultimate** scenario*

		Delta EV vs. VIPV Ultimate			
		HB11	HB12	HB22	HB23
		Low-floor bus		*High-floor bus*	
Factor	**Desired change**	Urban public transport service	*Peri urban public transport service*	*Regional public transport*	*Long-distance highway travel*
TCO [€ / 5 y]	↓	-832	-599	-1,046	-2,352
Payback period [Y]	↓	3.5	2.8	3.2	2.3
CO_2 emission [%][69]	↓	-	-	-	-
Autonomy	↑	0	0	0	0
Convenience	↑	7%	8%	0%	0%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	1	1	1	1
Parking location independency	↑	0	0	0	0

N5.4 Vehicle owner of trucks (HTXX)

This paragraph presents the valuation of costs and benefits for vehicle owners of trucks (HTXX).

ICE vs. VIPV

*Table 114: Vehicle owners of trucks (HTXX): Valuation of costs and benefits between **ICE** and **VIPV-ICE** in 2023*

Factor	Desired change	Delta ICE vs. VIPV 2023 HT11	HT12	HT22	HT23
		Rigid truck		*Tractor-trailer*	
		Urban distribution	*Regional distribution*	*Urban distribution*	*Regional distribution*
TCO [€ / 5 year]	↓	€-4,882	€-6,243	€-10,510	€-31,731
Payback period [years]	↓	1.7	1.6	1.8	0.9
CO_2 emission [%]	↓	5.5%	4.0%	8.3%	4.7%
Battery lifetime	↑	0	0	0	0
Noise reduction / comfort	↑	0	1	0	2
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

*Table 115: Vehicle owners of trucks (HTXX): Valuation of costs and benefits between **ICE** and **VIPV-ICE** in 2025*

Factor	Desired change	Delta ICE vs. VIPV 2025 HT11	HT12	HT22	HT23
		Rigid truck		*Tractor-trailer*	
		Urban distribution	*Regional distribution*	*Urban distribution*	*Regional distribution*
TCO [€ / 5 year]	↓	€-5,239	€-6,653	€-11,361	€-31,480
Payback period [years]	↓	1.5	1.4	1.5	0.8
CO_2 emission [%]	↓	5.5%	4.0%	8.3%	4.7%
Battery lifetime	↑	0	0	0	0
Noise reduction / comfort	↑	0	1	0	2
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

*Table 116: Vehicle owners of trucks (HTXX): Valuation of costs and benefits between **ICE** and **VIPV-ICE** in 2030*

Factor	Desired change	Delta ICE vs. VIPV 2030 HT11	HT12	HT22	HT23
		Rigid truck		*Tractor-trailer*	
		Urban distribution	*Regional distribution*	*Urban distribution*	*Regional distribution*
TCO [€ / 5 year]	↓	€-5,239	€-8,105	€-14,092	€-32,452
Payback period [years]	↓	1.1	1.0	1.1	0.7
CO_2 emission [%]	↓	6.2%	4.4%	9.2%	5.2%
Battery lifetime	↑	0	0	0	0
Noise reduction / comfort	↑	0	1	0	2
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

[69] The energy consumption of vehicle archetypes was not calculated for the Ultimate scenario in Task 1. As a result, CO_2 emission reductions related to decreased energy consumption are not included for the Ultimate scenario.

*Table 117: Vehicle owners of trucks (HTXX): Valuation of costs and benefits between **ICE** and **VIPV-ICE** in **Ultimate** timeframe*

		Delta ICE vs. VIPV Ultimate			
		HT11	HT12	HT22	HT23
		Rigid truck		*Tractor-trailer*	
Factor	**Desired change**	*Urban distribution*	*Regional distribution*	*Urban distribution*	*Regional distribution*
TCO [€ / 5 year]	↓	€-6,437	-9,434	-16,466	-32,664
Payback period [years]	↓	1.0	0.9	1.0	0.7
CO_2 emission [%][70]	↓	-	-	-	-
Battery lifetime	↑	2	2	2	2
Noise reduction / comfort	↑	0	1	0	2
Eco-friendly image	↑	1	1	1	1
Parking location independency	↑	0	0	0	0

EV vs. VIPV

*Table 118: Vehicle owners of trucks (HTXX): Valuation of costs and benefits between **EV** and **VIPV** in **2023***

		Delta EV vs. VIPV 2023			
		HT11	HT12	HT22	HT23
		Rigid truck		*Tractor-trailer*	
Factor	**Desired change**	*Urban distribution*	*Regional distribution*	*Regional distribution*	*Long-haul freight transport*
TCO [€ / 5 year]	↓	1,308	1,071	2,724	-1,094
Payback period	↓	>5	4.6	>5	2.8
CO_2 emission [%]	↓	-5%	-3%	-4%	-2%
Autonomy	↑	0	0	0	0
Convenience	↑	0%	0%	4%	1%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

*Table 119: Vehicle owners of trucks (HTXX): Valuation of costs and benefits between **EV** and **VIPV** in **2025***

		Delta EV vs. VIPV 2025			
		HT11	HT12	HT22	HT23
		Rigid truck		*Tractor-trailer*	
Factor	**Desired change**	*Urban distribution*	*Regional distribution*	*Regional distribution*	*Long-haul freight transport*
TCO [€ / 5 year]	↓	824	551	1645	-2,310
Payback period	↓	>5	>5	>5	3.8
CO_2 emission [%]	↓	-5%	-4%	-5%	-3%
Autonomy	↑	0	0	0	0
Convenience	↑	3%	0%	0%	3%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

[70] The energy consumption of vehicle archetypes was not calculated for the Ultimate scenario in Task 1. As a result, CO_2 emission reductions related to decreased energy consumption are not included for the Ultimate scenario.

*Table 120: Vehicle owners of trucks (HTXX): Valuation of costs and benefits between **EV** and **VIPV** in **2030***

		Delta EV vs. VIPV 2030			
		HT11	HT12	HT22	HT23
		Rigid truck		*Tractor-trailer*	
Factor	**Desired change**	*Urban distribution*	*Regional distribution*	*Regional distribution*	*Long-haul freight transport*
TCO [€ / 5 year]	↓	€123	€-242	€51	€-4,591
Payback period	↓	>5	4.6	>5	2.8
CO_2 emission [%]	↓	-6%	-5%	-7%	-3%
Autonomy	↑	0	0	0	0
Convenience	↑	0%	0%	0%	0%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

*Table 121: Vehicle owners of trucks (HTXX): Valuation of costs and benefits between **EV** and **VIPV** in **Ultimate** timeframe*

		Delta EV vs. VIPV Ultimate			
		HT11	HT12	HT22	HT23
		Rigid truck		*Tractor-trailer*	
Factor	**Desired change**	*Urban distribution*	*Regional distribution*	*Regional distribution*	*Long-haul freight transport*
TCO [€ / 5 year]	↓	-182	-619	-622	-5,957
Payback period	↓	4.7	4.1	4.5	2.5
CO_2 emission [%][71]	↓	-	-	-	-
Autonomy	↑	0	0	0	0
Convenience	↑	4%	0%	0%	0%
Range	↑	0	0	0	0
Battery lifetime	↑	0	0	0	0
Eco-friendly image	↑	2	2	2	2
Parking location independency	↑	0	0	0	0

[71] The energy consumption of vehicle archetypes was not calculated for the Ultimate scenario in Task 1. As a result, CO_2 emission reductions related to decreased energy consumption are not included for the Ultimate scenario.

M5.5 Policymaker

This paragraph presents the valuation of costs and benefits for policymakers.

*Table 122: Policymaker: Valuation of costs and benefits across scenarios in **2023***

Scenario		CO2 Reduction (% of total EU road emissions in 2022)
Name	**Description**	**2023**
Base	No uptake of VIPV	0%
Low Uptake	Low uptake of VIPV	0%
High Uptake	High uptake of VIPV	0%
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	0%

*Table 123: Policymaker: Valuation of costs and benefits across scenarios in **2025***

Scenario		CO2 Reduction (% of total EU road emissions in 2022)
Name	**Description**	**2025**
Base	No uptake of VIPV	0%
Low Uptake	Low uptake of VIPV	0%
High Uptake	High uptake of VIPV	0%
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	0%

*Table 124: Policymaker: Valuation of costs and benefits across scenarios in **2030***

Scenario		CO2 Reduction (% of total EU road emissions in 2022)
Name	**Description**	**2030**
Base	No uptake of VIPV	0%
Low Uptake	Low uptake of VIPV	0.01%
High Uptake	High uptake of VIPV	0.07%
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	0.07%

*Table 125: Policymaker: Valuation of costs and benefits across scenarios in the **Ultimate** timeframe*

Scenario		CO2 Reduction (% of total EU road emissions in 2022)[72]
Name	**Description**	**Ultimate**
Base	No uptake of VIPV	-
Low Uptake	Low uptake of VIPV	-
High Uptake	High uptake of VIPV	-
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	-

[72] The energy consumption of vehicle archetypes was not calculated for the Ultimate scenario in Task 1. As a result, potential revenue changes related to decreased electricity consumption from the grid are not included for the Ultimate scenario.

N5.6 Grid Operator

This paragraph presents the valuation of costs and benefits for grid operators.

Table 126: Grid Operator: Valuation of costs and benefits across scenarios in ***2023***

Scenario		Grid Utilisation	Investment in Infrastructure
Name	**Description**	**2023**	**2023**
Base	No uptake of VIPV	0	0
Low Uptake	Low uptake of VIPV	0	0
High Uptake	High uptake of VIPV	0	0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	0	0

Table 127: Grid Operator: Valuation of costs and benefits across scenarios in ***2025***

Scenario		Grid Utilisation	Investment in Infrastructure
Name	**Description**	**2025**	**2025**
Base	No uptake of VIPV	0	0
Low Uptake	Low uptake of VIPV	0	0
High Uptake	High uptake of VIPV	0	0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	0	0

Table 128: Grid Operator: Valuation of costs and benefits across scenarios in ***2030***

Scenario		Grid Utilisation	Investment in Infrastructure
Name	**Description**	**2030**	**2030**
Base	No uptake of VIPV	0	0
Low Uptake	Low uptake of VIPV	1	1
High Uptake	High uptake of VIPV	2	2
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	1	1

Table 129: Grid Operator: Valuation of costs and benefits across scenarios in ***Ultimate*** *timeframe*

Scenario		Grid Utilisation	Investment in Infrastructure
Name	**Description**	**Ultimate**	**Ultimate**
Base	No uptake of VIPV	0	0
Low Uptake	Low uptake of VIPV	0	0
High Uptake	High uptake of VIPV	1	1
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	0	0

N5.7 Charging Point Operator (CPO)

This paragraph presents the valuation of costs and benefits for charging point operators (CPOs).

*Table 130: Charging Point Operator (CPO): Valuation of costs and benefits across scenarios in **2023***

Scenario		Revenues [€/y]	Investment in Infrastructure (0-2)
Name	Description	2023	2023
Base	No uptake of VIPV	€0	0
Low Uptake	Low uptake of VIPV	€0	0
High Uptake	High uptake of VIPV	€0	0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	€0	0

*Table 131: Charging Point Operator (CPO): Valuation of costs and benefits across scenarios in **2025***

Scenario		Revenues [€/y]	Investment in Infrastructure (0-2)
Name	Description	2025	2025
Base	No uptake of VIPV	€0	0
Low Uptake	Low uptake of VIPV	€0	0
High Uptake	High uptake of VIPV	€0	0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	€0	0

*Table 132: Charging Point Operator (CPO): Valuation of costs and benefits across scenarios in **2030***

Scenario		Revenues [€/y]	Investment in Infrastructure (0-2)
Name	Description	2030	2030
Base	No uptake of VIPV	€0	0
Low Uptake	Low uptake of VIPV	-€54 million	0
High Uptake	High uptake of VIPV	-€533 million	0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	-€569 million	0

*Table 133: Charging Point Operator (CPO): Valuation of costs and benefits across scenarios in **Ultimate** timeframe*

Scenario		Revenues [€/y][73]	Investment in Infrastructure (0-2)
Name	Description	Ultimate	Ultimate
Base	No uptake of VIPV	-	0
Low Uptake	Low uptake of VIPV	-	0
High Uptake	High uptake of VIPV	-	0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	-	0

[73] The energy consumption of vehicle archetypes was not calculated for the Ultimate scenario in Task 1. As a result, potential revenue changes related to decreased electricity consumption from the grid are not included for the Ultimate scenario.

N5.8 Energy Company

This paragraph presents the valuation of costs and benefits for energy companies.

*Table 134: Energy Company: Valuation of costs and benefits across scenarios in **2023***

Scenario		Revenues [€/y]
Name	**Description**	**2023**
Base	No uptake of VIPV	€0
Low Uptake	Low uptake of VIPV	€0
High Uptake	High uptake of VIPV	€0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	€0

*Table 135: Energy Company: Valuation of costs and benefits across scenarios in **2025***

Scenario		Revenues [€/y]
Name	**Description**	**2025**
Base	No uptake of VIPV	€0
Low Uptake	Low uptake of VIPV	€0
High Uptake	High uptake of VIPV	€0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	€0

*Table 136: Energy Company: Valuation of costs and benefits across scenarios in **2030***

Scenario		Revenues [€/y]
Name	**Description**	**2030**
Base	No uptake of VIPV	€0
Low Uptake	Low uptake of VIPV	-€88 million
High Uptake	High uptake of VIPV	-€858 million
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	-€917 million

*Table 137: Energy Company: Valuation of costs and benefits across scenarios in **Ultimate** timeframe*

Scenario		Revenues [€/y][74]
Name	**Description**	**Ultimate**
Base	No uptake of VIPV	-
Low Uptake	Low uptake of VIPV	-
High Uptake	High uptake of VIPV	-
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	-

[74] The energy consumption of vehicle archetypes was not calculated for the Ultimate scenario in Task 1. As a result, potential revenue changes related to decreased electricity consumption from the grid are not included for the Ultimate scenario.

N5.9 Solar Solution Manufacturer

This paragraph presents the valuation of costs and benefits for solution manufacturers.

Table 138: Solar Solution Manufacturer: Valuation of costs and benefits across scenarios in ***2023***

Scenario		Revenues [€/y]
Name	**Description**	**2023**
Base	No uptake of VIPV	€0
Low Uptake	Low uptake of VIPV	€0
High Uptake	High uptake of VIPV	€0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	€0

Table 139: Solar Solution Manufacturer: Valuation of costs and benefits across scenarios in ***2025***

Scenario		Revenues [€/y]
Name	**Description**	**2025**
Base	No uptake of VIPV	€0
Low Uptake	Low uptake of VIPV	€0
High Uptake	High uptake of VIPV	€0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	€0

Table 140: Solar Solution Manufacturer: Valuation of costs and benefits across scenarios in ***2030***

Scenario		Revenues [€/y]
Name	**Description**	**2030**
Base	No uptake of VIPV	€0
Low Uptake	Low uptake of VIPV	+€418 million
High Uptake	High uptake of VIPV	+€1,645 million
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	+€1,784 million

Table 141: Solar Solution Manufacturer: Valuation of costs and benefits across scenarios in Ultimate timeframe

Scenario		Revenues [€/y][75]
Name	**Description**	**Ultimate**
Base	No uptake of VIPV	-
Low Uptake	Low uptake of VIPV	-
High Uptake	High uptake of VIPV	-
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	-

[75] The energy consumption of vehicle archetypes was not calculated for the Ultimate scenario in Task 1. As a result, potential revenue changes related to decreased electricity consumption from the grid are not included for the Ultimate scenario.

N5.10 OEM / Car Manufacturer

This paragraph presents the valuation of costs and benefits for OEM / Car manufacturers.

Table 142: OEM / Car Manufacturer: Valuation of costs and benefits across scenarios in ***2023***

Scenario		Revenues [€/y]	Brand Image [0-2]	Regulatory Compliance [0-2]
Name	**Description**	**2023**	**2023**	**2023**
Base	No uptake of VIPV	€0	0	0
Low Uptake	Low uptake of VIPV	€0	0	0
High Uptake	High uptake of VIPV	€0	0	0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	€0	0	0

Table 143: OEM / Car Manufacturer: Valuation of costs and benefits across scenarios in ***2025***

Scenario		Revenues [€/y]	Brand Image [0-2]	Regulatory Compliance [0-2]
Name	**Description**	**2025**	**2025**	**2025**
Base	No uptake of VIPV	€0	0	0
Low Uptake	Low uptake of VIPV	€0	0	0
High Uptake	High uptake of VIPV	€0	1	0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	€0	1	0

Table 144: OEM / Car Manufacturer: Valuation of costs and benefits across scenarios in ***2030***

Scenario		Revenues [€/y]	Brand Image [0-2]	Regulatory Compliance [0-2]
Name	**Description**	**2030**	**2030**	**2030**
Base	No uptake of VIPV	€0	0	0
Low Uptake	Low uptake of VIPV	+€1,209 million	0	0
High Uptake	High uptake of VIPV	+€2,742 million	2	0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	+€2,973 million	2	2

Table 145: OEM / Car Manufacturer: Valuation of costs and benefits across scenarios in ***Ultimate*** *timeframe*

Scenario		Revenues [€/y][76]	Brand Image [0-2]	Regulatory Compliance [0-2]
Name	**Description**	**Ultimate**	**Ultimate**	**Ultimate**
Base	No uptake of VIPV	-	0	0
Low Uptake	Low uptake of VIPV	-	1	0
High Uptake	High uptake of VIPV	-	1	0
High Uptake Plus	High uptake of VIPV & accelerated EV uptake	-	1	2

[76] The energy consumption of vehicle archetypes was not calculated for the Ultimate scenario in Task 1. As a result, potential revenue changes related to decreased electricity consumption from the grid are not included for the Ultimate scenario.

Appendix O: Relevant EU policies

Appendix P provides the introductory texts published by the EU on each regulation mentioned in paragraph 3.5.1.

Fit for 55

Light-duty vehicles

Source: : https://climate.ec.europa.eu/eu-action/transport-decarbonisation/road-transport/light-duty-vehicles_en

> Passenger cars and light commercial vehicles (vans) are respectively responsible for around 16% and 3% of total EU emissions of carbon dioxide (CO_2), the main greenhouse gas driving climate change.
>
> To help reduce emissions, the EU has a Regulation that sets CO_2 emission performance standards for new passenger cars and vans (Regulation (EU) 2019/631).
>
> With stricter CO_2 emission targets in place since 2020, the average CO_2 emissions from all new passenger cars registered in Europe fell by 27% between 2019 and 2022, while the average emissions from new vans dropped by 10%. The main driver of this decrease in emissions is the surge in zero-emission vehicles, which respectively amounted to 13.4% and 6% of the 2022 EU (and Norway and Iceland) new car and van fleet.
>
> On 19 April 2023, the European Parliament and the Council amended the Regulation to strengthen the CO_2 emission performance standards for new passenger cars and vans, and bring them in line with the EU's ambition to reach climate neutrality by 2050. This amendment strengthened the emission targets applying from 2030 and set a 100% emission reduction target for both cars and vans from 2035 onwards.

CO_2 emission standards for heavy-duty vehicles

Source: https://climate.ec.europa.eu/eu-action/transport-decarbonisation/road-transport/heavy-duty-vehicles_en

> HDVs are responsible for more than a quarter of greenhouse gas (GHG) emissions from road transport in the EU, and for over 6% of total EU GHG emissions. In the context of the European Green Deal, the EU has adopted emission standards for HDVs, which will become increasingly strict over time. By lowering demand for fossil fuels, as well as strengthening the development and adoption of zero-emission technologies, these standards support the EU's transition to a clean and sustainable transport system.
>
> According to the Regulation on CO_2 emission standards for HDVs, manufacturers will have to comply with targets for fleet-wide average CO_2 emissions starting from 2025. These targets will apply to new HDVs registered in the reporting period of a given year, namely from 1 July of that year to 30 June of the following year.
>
> The first-ever EU-wide CO_2 emission standards for HDVs were established by Regulation (EU) 2019/1242, which set a 15% reduction target by 2025. Adopted in 2019, these standards are applicable to heavy lorries over 16 tonnes with standard axle configurations, which account for approximately 70% of the CO_2 emissions produced by all HDVs.

As part of the 'Fit for 55' legislative package, the emission standards for HDVs set by Regulation (EU) 2019/1242 were revised. The amendments to the Regulation entered into force on 26 June 2024.

The amended Regulation has a wider scope, covering nearly all emissions from HDVs as it applies not only to heavy lorries but also to medium lorries, city buses, coaches, and trailers. As illustrated below, the revised targets are also more ambitious, aiming for increasing CO_2 emission reductions in the coming decades:

- 45% by 2030
- 65% by 2035
- 90% by 2040

The revised targets require a percentage reduction of emissions across all vehicles manufactured by a company during a certain reporting period, compared to the EU average of vehicles registered in a specific reference period. The reporting periods of the following years are applicable as reference periods:

- 2019 for vehicles regulated under previous standards;
- 2021 for newly regulated lorries above 7,5 tonnes, as well as lorries with special axle configurations above 16 tonnes;
- 2025 for coaches, trailers, and medium lorries between 5 and 7,5 tonnes.

To reduce transport emissions in urban areas, the amended Regulation mandates that 90% of new city buses must be zero-emission by 2030 and, as of 2035, all new city buses will have to meet the same requirements. Moreover, starting in 2030, CO_2 emissions must be reduced by 10% for new semi-trailers and by 7.5% for new trailers other than semi-trailers.

For trailers, a CO_2 reduction of 15% in 2025 and 30% in 2030 (reference year: 2019) is required.

VECTO

Source: https://climate.ec.europa.eu/eu-action/transport-decarbonisation/road-transport/vehicle-energy-consumption-calculation-tool-vecto_en

VECTO is the simulation tool developed by the European Commission to determine CO_2 emissions and fuel consumption from heavy-duty vehicles. As of January 2019, the use of VECTO has been gradually extended to cover an increasing number of vehicle groups:

- heavy lorries with standard axle configurations
- medium lorries
- lorries with specific axle configurations
- buses and coaches

A variety of mission profiles for lorries, buses and coaches have been developed and incorporated into the tool. VECTO is available as a downloadable executable file designed for use on a single computer.

VECTO relies on characteristic parameters to determine the power consumption of each relevant vehicle component, including rolling resistance, air drag, masses and inertias, gearbox friction, auxiliary power, and engine performance. These input values are used to simulate CO2 emissions and fuel consumption on standardised driving cycles.

CO_2 emissions and fuel consumption data determined with VECTO must be monitored and reported to the Commission by Member States and manufacturers, and made publicly available for new trucks.

Alternative Fuels Infrastructure Regulation (AFIR)

Source: https://transport.ec.europa.eu/transport-themes/clean-transport/alternative-fuels-sustainable-mobility-europe/alternative-fuels-infrastructure_en

In the context of the ‘Fit for 55’ package, the co-legislators agreed on a new Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure repealing Directive 2014/94/EU. The regulation is applicable since 13 April 2024.

The specific objectives of the Regulation are:

- to ensure minimum infrastructure to support the required uptake of alternative fuel vehicles across all transport modes and in all EU Member States to meet the EU’s climate objectives;
- to ensure full interoperability of the infrastructure; and
- to ensure comprehensive user information and adequate payment options at alternative fuels infrastructure.

The regulation sets a number of mandatory national targets for the deployment of alternative fuels infrastructure in the EU, for road vehicles, vessels and stationary aircraft.

For publicly available electric recharging infrastructure for light duty road vehicles (cars and vans), the regulation sets out mandatory national fleet based power targets (e.g. for every battery electric light duty vehicle a total power output of at least 1.3 kW must be provided through publicly accessible recharging stations while for every plug-in hybrid light-duty vehicle, a total power output of at least 0.8 kW must be provided). It also sets out distance-based targets for light duty and heavy-duty road vehicles on the Trans-European Transport Network (TEN-T) core and comprehensive network. It also requires EU Member States to ensure a number of recharging stations are in place for heavy-duty vehicles in urban nodes and in safe and secure parkings.

The regulation also includes provisions for ensuring user-friendliness of recharging infrastructure (e.g. payment options, price transparency and consumer information, non-discriminatory practices, smart recharging).

Net-Zero Industry Act

Source: https://commission.europa.eu/topics/competitiveness/green-deal-industrial-plan/net-zero-industry-act_en

The Net-Zero Industry Act is an initiative stemming from the Green Deal Industrial Plan which aims to scale up the manufacturing of clean technologies in the EU. This means increasing the EU’s manufacturing capacity of technologies that support the clean energy transition and release extremely low, zero or negative greenhouse gas emissions when they operate.

> This Act will attract investments and create better conditions and market access for clean tech in the EU. The aim is that the Union's overall strategic net-zero technologies manufacturing capacity approaches or reaches at least 40% of annual deployment needs by 2030. This will accelerate the progress towards the EU's 2030 climate and energy targets and the transition to climate neutrality by 2050. It will also boost the competitiveness of EU industry, create quality jobs, and support the EU's efforts to become energy independent.

EU Competitiveness Compass

Source: https://commission.europa.eu/topics/competitiveness/competitiveness-compass_en

> Over the last two decades, Europe's potential has remained strong, even as other major economies have grown at a faster pace.
>
> The EU has everything it takes to unlock its full potential and drive faster, more sustainable growth: we boast a talented and educated workforce, capital, savings, the single market, and a unique social model. To restore our competitiveness and unleash growth, we need to tackle the barriers and weaknesses that are holding us back.
>
> In January 2025, the Commission presented the competitiveness compass, a new roadmap to restore Europe's dynamism and boost our economic growth.
>
> The compass builds on the analysis of Mario Draghi's report on the future of European competitiveness.
>
> The Draghi report originally identified three necessities for the EU to boost its competitiveness:
>
> 1. Closing the innovation gap
> 2. Decarbonising our economy
> 3. Reducing dependencies
>
> The compass sets out an approach to translate these necessities into reality.
>
> *Closing the innovation gap*
> The compass spells out how the European Union will boost innovation by:
>
> - creating a friendly environment for young companies to start and expand, with a dedicated EU start-up and scale-up strategy
> - helping big companies adopt new technologies such as artificial intelligence (AI) and robotics, thanks to our Apply AI strategy
> - making it easier for companies to operate across the EU by simplifying rules and laws, with a proposal for a 28th legal regime that will guarantee one set of rules across the EU
> - supporting the development of new technologies, with action plans for quantum, advanced materials, biotech, robotics and space technologies
>
> *Decarbonising our economy*
> The compass sets out how we can shift to clean and affordable energy by:
>
> - putting forward the Clean Industrial Deal, to help reduce carbon emissions, especially for energy intensive companies, and facilitate their transition to low carbon technologies

- presenting tailor-made action plans for energy intensive sectors, such as chemicals, steel and metals, which are the most vulnerable at this phase of the transition
- developing an affordable energy action plan to help bring down energy prices and costs

Reducing dependencies
The EU already has the largest and fastest growing network of trade agreements in the world, covering 76 countries. The compass identifies how we can further diversify and strengthen our supply chains by:

- developing a new range of clean trade and investment partnerships to help secure supply of raw materials, clean energy, sustainable transport fuels, and clean tech from across the world; the first such partnership was signed with South Africa in November 2025
- reviewing the public procurement rules to allow for the introduction of a European preference in public procurement for critical sectors and technologies