SolarMoves: Modelling the impact of vehicle integrated photovoltaics on the electricity grid

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List of abbreviations and Definitions

BEV: Battery Electrical Vehicle

BigEye: PV system simulation tool by TNO.

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

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

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

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

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

GHG: Greenhouse Gas

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

GIS: Geographic Information system

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)

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.

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

PV: Photovoltaics

PV on sun facing surfaces: PV on the roof, hood and boot (where possible)

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

TCO: Total Cost of Ownership

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

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.

Table 1: 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 periurban 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 periurban commute’
LP23	LD	Medium sized passenger car	‘long-distance highway travel’
LP31	LD	SUV	‘daily urban commute’
LP32	LD	SUV	‘daily periurban commute’
LP33	LD	SUV	‘long-distance highway travel’
LV11	LD	Small van	‘Local distribution’
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Executive Summary

This document reports on the activities that were carried out in the first phase of the SolarMoves project, a tender project commissioned by DG MOVE. A desktop study was carried out 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; (see Figure 1).

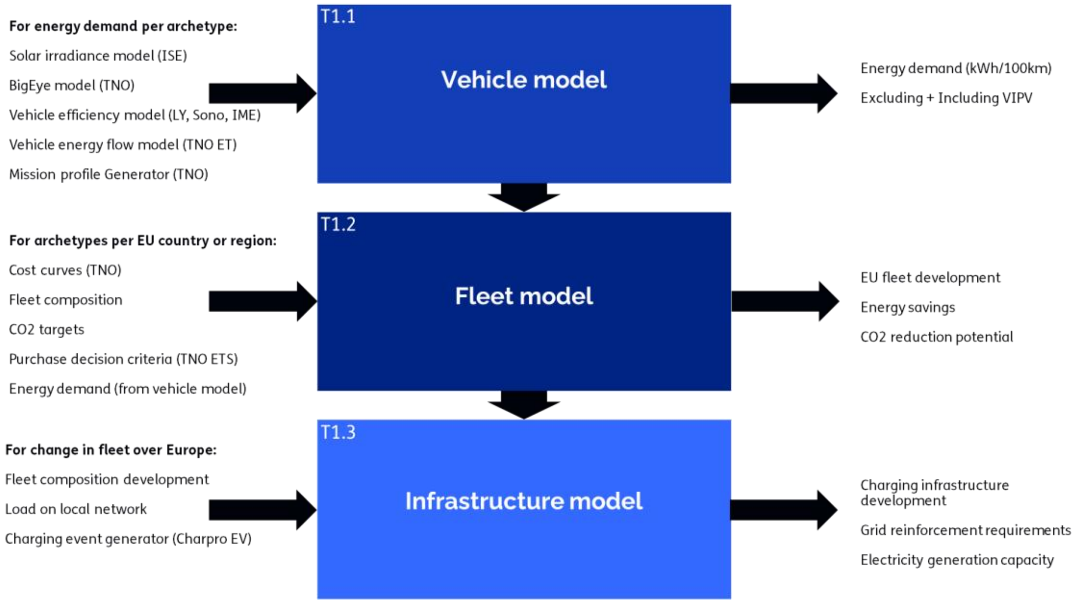

Figure 1: General model diagram with inputs and required outputs from different system level models

A large number of input variables was needed to address all aspects of these simulations as seen in Figure 1. For this, public data was collected to define average types of vehicles, energy consumption, driving patterns, charging behaviour, weather and shading effects.

With the vehicle model the impact of VIPV and other energy saving options on energy consumption and costs was determined for 23 different electric vehicle – user-pattern combinations or “archetypes” (Table 1). The fleet model was then build from these archetypes and was based on data of the Dutch fleet and was used to make predictions on the fleet composition, the energy savings and the CO_2 emission savings in 2025 and 2030 at the fleet level using the results of the vehicle model as input. Finally, the infrastructure model was used to predict the potential impact of VIPV on the required charging infrastructure on a local neighbourhood level as this would represent the most localized level of energy management.

The vehicle modelling shows that VIPV has the largest impact for light vehicles with low annual mileage. For small passenger cars, VIPV can generate up to 55% of the annual energy consumption in Amsterdam and up to 80% in Madrid. For heavier vehicles with a higher annual mileage the impact of VIPV is less. It is estimated that for electric vans, VIPV can produce about 15-30 % of the energy consumption. The contribution of VIPV drops to 2-4% for busses and long distance trucks.

The impact of additional energy saving options (like reduction of rolling resistance and air drag) scales linearly with the annual mileage and is therefore larger for trucks and buses. Combined with VIPV they can lead to a reduction in energy consumption of more than 20% for long distance trucks.

Overall, the simulations on the vehicle level suggest that VIPV offers a significant reduction in energy consumption. We see that the potential contribution of VIPV to reduce external energy demand in the 2030 timeframe is at least as significant as that of all other energy consumption reduction options combined (and in most cases larger).

At the fleet level, the expected evolution of more efficient electric vehicles can lead to a reduction in grid energy demand by as much as 25 TWh per year in 2030 where VIPV could contribute to more than 50% of this energy savings. However, it may not always be economically viable for the first owner (5 years) at present time due to the still high additional cost of a VIPV system.

From a societal perspective, though, VIPV could have a significant positive impact on the required infrastructure that is provided for a fully electrified road transport.

The benefits of VIPV need to be considered from two perspectives. From the perspective of the end user the benefits are: less charging moments (higher driving range security), less charging costs. Presently, the charging cost savings are not or hardly in balance with the higher investment costs for VIPV. From a societal perspective , though, VIPV could have a significant positive impact on the required infrastructure that is foreseen for a fully electrified road transport. VIPV could act as a supplement to other necessary actions (staged ("smart") charging and grid capacity expansion) and reduce the effort needed for these actions.

Vehicle Level Assessment:

- VIPV showcases varied energy generation potential across vehicle types, efficiency levels, locations, and usage patterns.
- For Southern European locations like Madrid, the most common passenger vehicle type (medium size, peri-urban use) VIPV could contribute up to 50% of the annual energy need.
- In Central European locations like the Netherlands, this would drop to about 35%.
- Simulations suggest that passenger cars on urban profiles in southern locations can achieve up to 60%-70% energy contribution, contrasting with long highway trips where the contribution is around 23%.
- VIPV proves advantageous for passenger cars with low annual mileage, rivalling or surpassing the potential of combined rolling resistance and air drag reduction measures.
- For higher mileage vehicles, particularly trucks and buses, the absolute amount of energy savings per vehicle can be 40x higher as compared to passenger cars due to the larger area available for solar installation.

Vehicle Efficiency Measures Adoption Rate:

- The adoption rate of VIPV and other vehicle efficiency improvements adoption is contingent on vehicle manufacturers, fleet operators, or initial owners opting to pay for the upfront cost of these technologies.
- Currently, with contemporary electricity costs, based on a return on investment in the first 5 years of ownership, VIPV is not financially attractive for the archetypes studied. Other efficiency measures are more financially attractive.
- However, as total cost of ownership is not significantly changed by the addition of VIPV, the other less economic benefits (societal, convenience, flexibility) could have a larger influence on adoption rates.

Fleet Level Impacts:

- A projection for EU27's EV fleet towards 2025 and 2030 anticipates as much as 27 TWh energy demand avoided due to efficiency measures, with VIPV contributing significantly.

- Through this offset of grid electricity and the present day average carbon intensity, between 1 Mton (2025) and 3 Mton (2030) per year of CO2-equivalent emissions could be avoided as compared to a fully electric fleet with no VIPV.

Grid Impact:

- VIPV implementation addresses local grid congestion issues, with a potential impact comparable to a 25% increase in local transformer capacity.
- VIPV does not eliminate the risk of excess demand events, necessitating smart charging strategies.
- Reduction in annual charging moments on the order of 10%-15% is likely leading to a potential decrease in the need for individual charging locations.

Key Conclusions:

- While VIPV presents convenience, infrastructure, and environmental benefits, financial constraints may impede widespread adoption, especially for passenger cars.
- Owners of larger vehicles, with a commercial use, may find VIPV more attractive, influenced by factors like logistics flexibility and additional range.
- Comprehensive policy incentives combining energy reduction measures and VIPV could significantly enhance the adoption of fully electric transport.
- The report acknowledges the simulation's narrow assumptions and highlights the importance of real-world validations to better understand VIPV's true potential. The SolarMoves consortium will continue refining these analyses for a more nuanced understanding of VIPV's impact.

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 of 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 actually 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. This interim report for the Project SolarMoves presents a methodical desk study based on state-of-the-art models at the level of PV, vehicle systems, and vehicle fleets as input for simulations at local and national grid level to better understand how large of a contribution on-board solar can make to the solving the challenges that stakeholders are facing in realizing the energy transition.

This report is structured in accordance with the progression of impacts on vehicle level energy efficiency, fleet composition, and the impact on grid infrastructure. In Chapter 1, the overall methodology is presented including the definitions of vehicle types, use patterns, and how these are combined to create specific archetypes. In Chapter 2, we present initial results from the modelling in terms of impacts on energy demand and energy efficiency for both VIPV and other innovations. Subsequently, in Chapter 3 we look at the modelled impact on fleet composition and financial viability and tradeoffs of different energy efficiency improvements, and we discuss the modelled impact on the grid at neighbourhood and country level. Finally, in Chapter 3, we look at the overall modelled results and discuss the possible impact of VIPV. Chapter 4 gives an overview of the progress of the project and gives a look ahead to the on-road testing and model validation of Task 2.

[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.

1. Methodology

The objectives of Task 1 were 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 goals objectives of Task 1 are to:

1. Determine the potential of energy consumption reduction options in EVs (including VIPV) (Subtask 1.1)
2. Obtain insight in the impact of energy consumption reduction options on the development of the fleet composition in Europe between 2025 and 2030 (Subtask 1.2)
3. Assess the implications for the development of charging infrastructure and integration in the electricity network (Subtask 1.3)

The contents of the Task, logically structured along the vehicle level, fleet level and infrastructure level (T1.1, T1.2, and T1.3) 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.

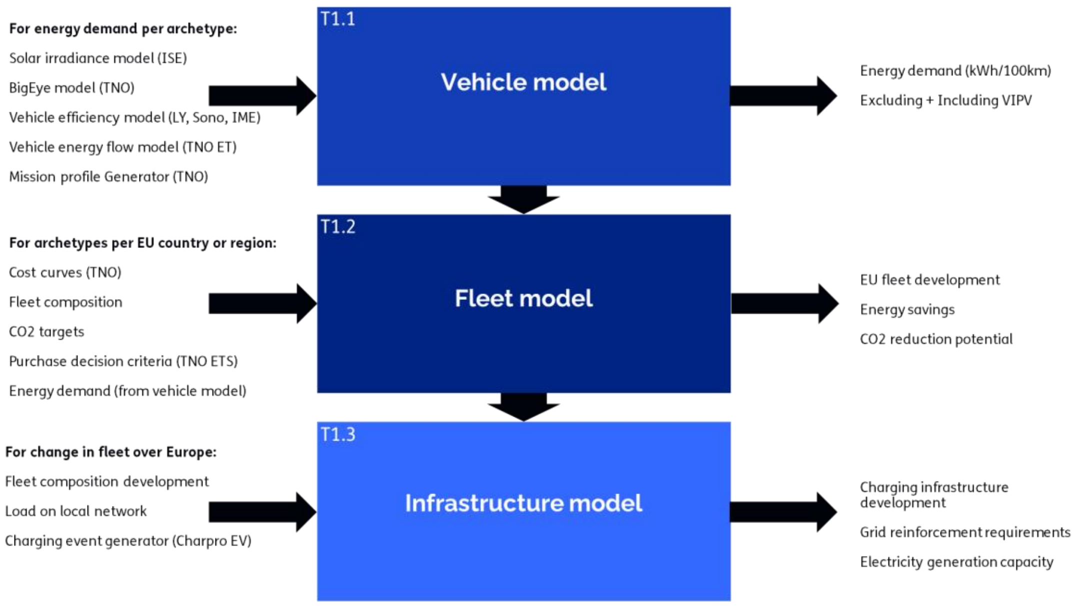

Figure 2: General model diagram with inputs and required outputs from different system level models

The results of Task 1 will be 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):
    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)

- A.2 Cost effective* 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 referred to at point DB.
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.

*) Cost effective in this case means: lower costs for the first owner of the vehicle.

To keep the work and results in Task 1 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 1.1.1.1, are the basis for the vehicle model, the fleet model and the infrastructure model.

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

1.1.1. Workflow of the Vehicle Model

The workflow for task 1.1 is depicted in Figure 3, where the following steps can be indicated:

1. Define of 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

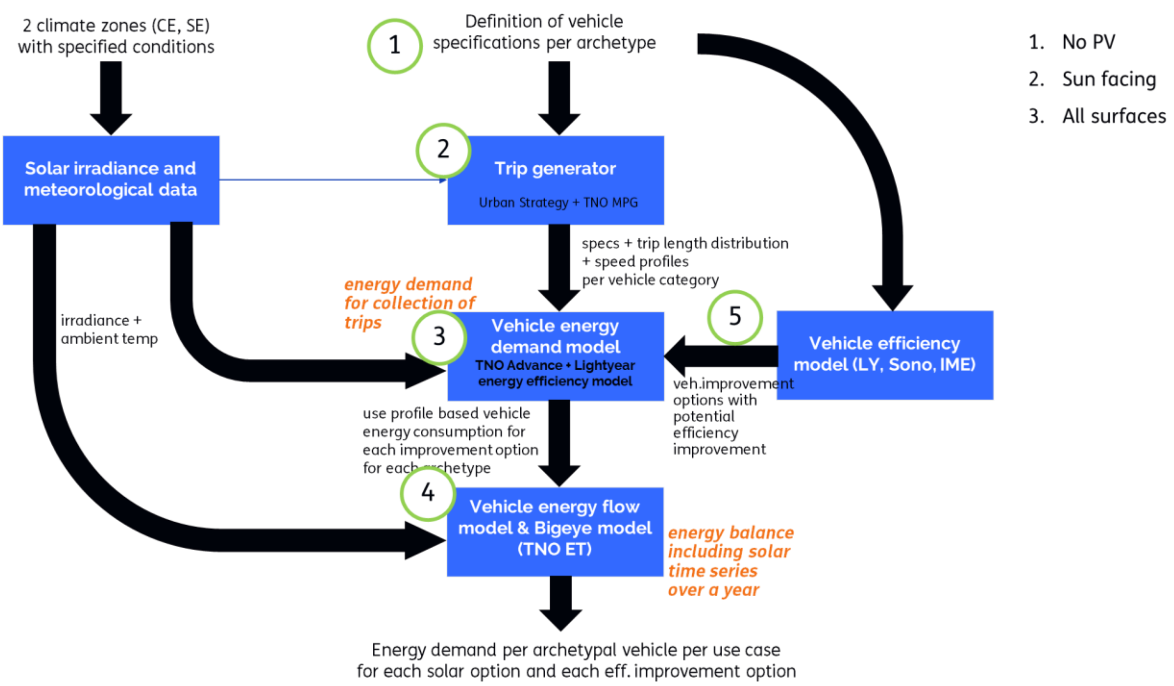

Figure 3: Workflow for Task 1.1

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.

1.1.1.1. 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. These archetypes have already been specified in the inception report but one archetype was added, namely LP10: small passenger car with occasional use. This was decided to cover the considerable share of vehicles in the fleet that are not used on a daily basis, such as second cars in a household. For the assumed irregular use pattern, the effect of VIPV on charging is different than for commuter type use patterns such as LP11. The resulting list of vehicle archetypes can be found in Table 2. The added archetype is indicated in **blue.** 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: 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 periurban 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 periurban commute’
LP23	LD	Medium sized passenger car	‘long-distance highway travel’
LP31	LD	SUV	‘daily urban commute’
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HT22	HD	Tractor-trailer	‘Regional distribution’
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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.

1.1.1.2. 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.

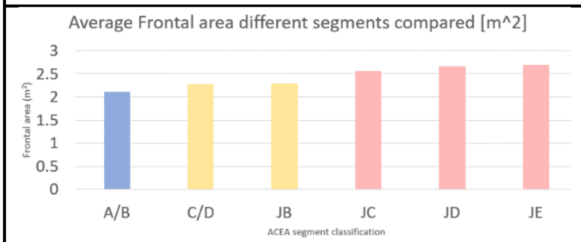
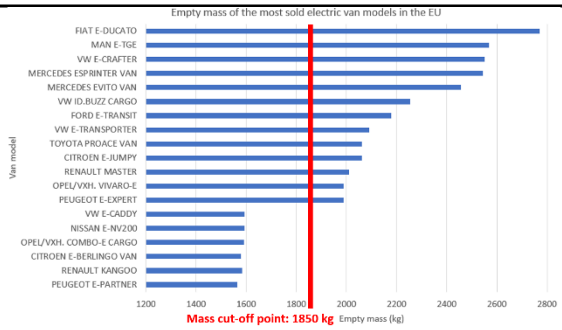
The characteristics were determined in a three-step approach:

1) Create the *types* for each vehicle class; this leads to distinguishing properties for each vehicle type in Table 2 (e.g. small van - large van)
2) Derive properties for each of the vehicle types based on the presently most common vehicle brands/models/variants in the fleet
3) 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 3.

Table 3 From vehicle class to vehicle type

Passenger cars	Vans
 ***Figure 3: Frontal areaof the different categories compared. Small (blue), medium (yellow), SUV (red)*** The definition of small, medium and SUV passenger cars is almost the same as the ACEA classification[2], 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.	 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.
Trucks	Buses
Currently, there aren't many electric trucks deployed yet. The characteristics are based on the electric models of the brands Volvo,	The characteristics of the low-floor bus are based on the average characteristics of the top 8 most registered electric buses in the

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

Mercedes, DAF and Renault. Together, these companies represent 60% of the conventional market.	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 4.

Table 4. 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[3]. 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[4]. 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.

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 Section 1.1.2.

[3] opendata.rdw.nl, 'basisregistratie voertuigen'
[4] ev-database.org

1.1.1.3. Charging losses and other non-use related consumption

In order to determine the AC charging losses, various documents were studied. In the report by van Gijlswijk et al.[5] 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. [6] come to roughly similar numbers[7] between 12.8 and 20.4%. The Dutch National Automotive Association (ANWB) report an average number of 15%.[8] The German national automotive association reports measured numbers between 12.7 and 24.2%.[9]
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. Only one paper was found mentioning charging losses of around 10% (at 25 deg C) [10]. 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.

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[5] 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
[6] 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
[7] 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
[8] https://www.anwb.nl/auto/elektrisch-rijden/opladen/laadverlies-thuisladen-elektrische-auto
[9] https://www.adac.de/rund-ums-fahrzeug/elektromobilitaet/laden/ladeverluste-elektroauto-studie/
[10] Energies | Free Full-Text | Evaluation of Fast Charging Efficiency under Extreme Temperatures (mdpi.com)

1.1.1.4. Charging

Boundaries are set to minimum and maximum battery state of charge in normal use, see Table 5. The table also shows the efficiency of the vehicle integrated PV.

Table 5: 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. W**hen using the charging strategy for optimising PV, the maximum SoC is lower**, see paragraph 1.1.5.2
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, in close collaboration with Task 2.

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

1.1.2.1. 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[11,12] by function: catering/fresh for LV11, single-piece delivery for LV12, mail and packages for LV21, and construction for LV22.

[11] Bokhorst, M. van et al, Van use in Europe and their environmental impact, CE Delft, September 2017
[12] 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 considered to be 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.

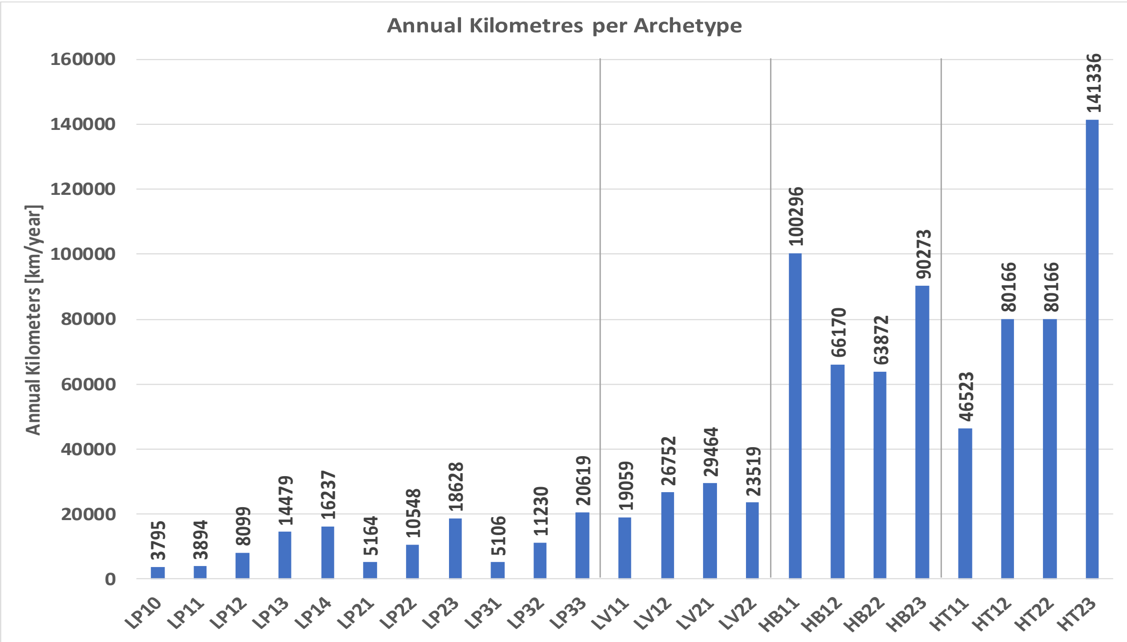


Figure 4: Annual kilometres per vehicle archetype.

1.1.2.2. Road types and trip length

As mentioned in 1.1.1.2 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.

1.1.2.3. 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

1.1.3.1. 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[13], where the models and the methods have been described in great detail. The steps are shown in the schematic in Figure 5 where the vehicle drives a trip from an origin to a destination.

[13] 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.

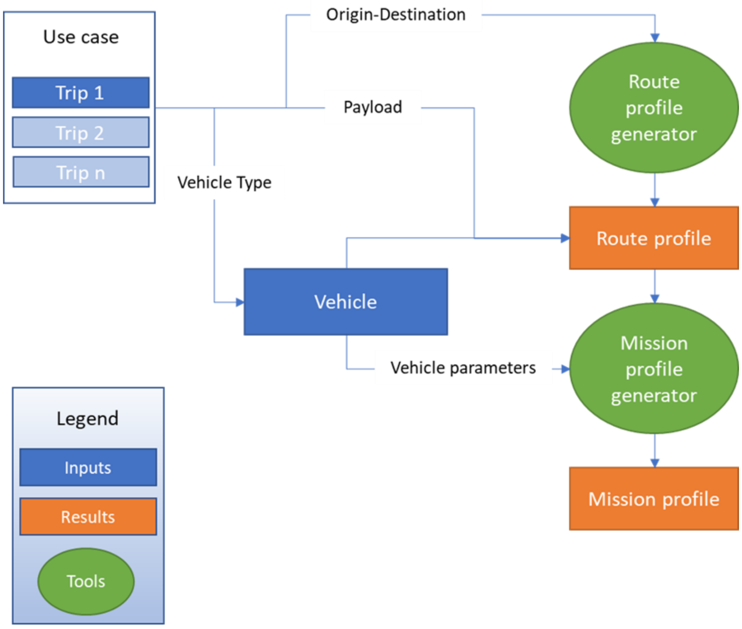


Figure 5.A schematic overview of the route and mission profile generator, the inputs needed, thereby showing a single trip formation

Each step is described below:

- Based on the origin and destination (and possibly 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[14] 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.
- 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 6.

Table 6. 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

[14] https://www2.jpl.nasa.gov/srtm/

1.1.3.2. 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. 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 7. These values are needed for e.g. regenerative braking, and are (when combined) in line with the values for grid charging in Section 1.1.1.3.

Table 7. 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

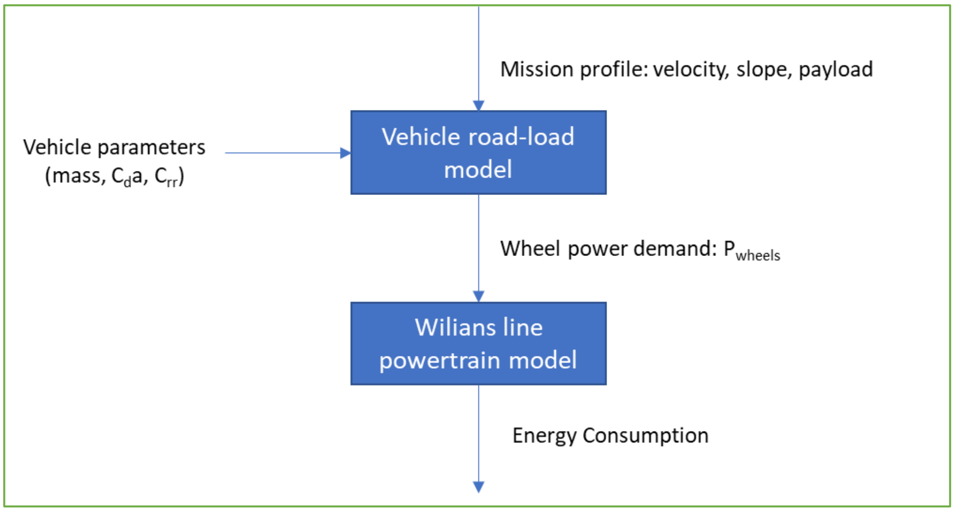


Figure 6: Schematic of the MEO model

1.1.3.3. 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 F.

1.1.3.4. 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, of which the length 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[15]. 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.

1.1.3.5. 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. Details are too elaborate to include in this report, but may be shared as Excel files in a later stage.

1.1.4. Trip definitions

1.1.4.1. 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

1.1.4.2. 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.

[15] 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 travel (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.

1.1.4.3. Trip definitions for each archetype

Below an overview is given 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 Trip definitions.

Table : 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 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%

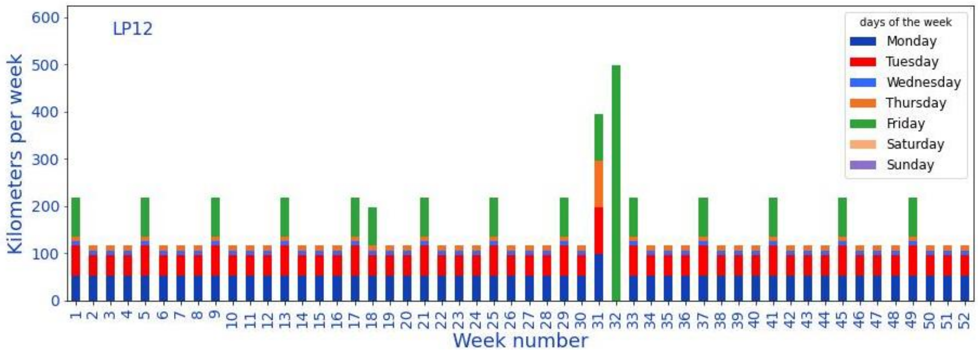


Figure 7: Example driving profile over the year for LP12. Showing weekly kilometres driven, with the different colours representing the days of the week. On the x-axis are the weeks of the year.

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

1.1.5. Vehicle Energy Flow Model & BigEye

1.1.5.1. 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.

1.1.5.2. 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 8. Note that the (highway) fast charge rates correspond to charging from 10% to 75% in 30 minutes, in other words: 1.3C (see Section 1.1.3.4). The rates are capped to 389 kW, corresponding to 350 kW after losses.

Table 8: VIPV-related vehicle specifications provided by Task 1.1 for use in EFM. 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 – this provides input for Task 1.3. The split between work and street charging is also included for T1.3

		Available PV area [m^2]		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

1.1.5.3. 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

1.1.5.4. Energy yield calculations

For calculations of the PV energy yield, the TNO built BigEye model is used. It was developed 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 [16] . For vehicles, a shading function is added to take into account. This will be explained in more detail in the next paragraph.

1.1.5.5. Shading function

There is not much information on the shading on cars induced by buildings and trees along roads. The thesis of Cobbenhagen[17] showed some measurement results, with a sinusoidal seasonal distribution of the daily average shading 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.[18] 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 to take into account the fact that in the Netherlands you hardly have completely open areas and the Urban routes are often a mix between real city center and more low-rise residential parts. The seasonal shading factors are shown in Figure 8 and result in an average annual shading loss of:

- Urban: 35%
- Semi-urban: 24%
- Motorway: 15%

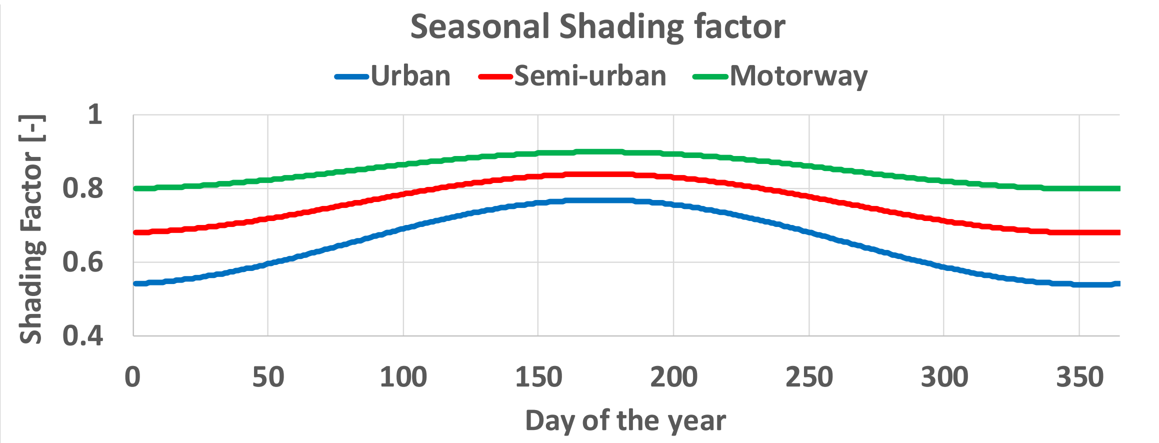


Figure 8: Seasonal shading factor for different road types. The shading factor is the fraction of the solar light received by the VIPV during a trip on a certain road type in comparison to the amount of solar light received on a trip without any shading losses.

[16] A.R. Burgers, BIGEYE - simulation under shadow conditions, presented at the 6th Workshop on Bifacial PV, Amsterdam (Sep. 2019)

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

[18] 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.

1.2. Task 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 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 was 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, that 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 9 gives an overview of the TCO parameters and assumptions for the different archetypes and Table 10 and Table 11 provide an overview of present and future costs of VIPV for passenger cars, trucks and buses.

Table 9: 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 is based on an EV cost development study by ICCT in 2022 [19].</td><td>Trucks prices and price development based on methodology in T&E study[20]. Electric bus price based on the known price in 2019 [21] and applying battery price development from T&E study[20].</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) [20].</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 [22] 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 [23]</td><td>HTxx: €0.132 / km [20]
HBxx: €0.15 / km [23]</td></tr>
<tr><td>Insurance costs</td><td>Varies based on purchase price [24]
On average €800 / year</td><td>HT1x: €3200/year, HT2x: €2000/year [23]
HBxx: €2000/year [23]</td></tr>
<tr><td>Taxes</td><td>EV taxes are near zero for most EU countries. Average ownership tax is €40 per year. [25]</td><td>Road tolling per km and per year is included for HTxx [20], 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% [26]
Business perspective (LVxx, HTxx, HBxx): discount rate of 8.0% [27]</td></tr>
</table>

[19] ICCT (2022). Assessment of light-duty electric vehicle costs and consumer benefits in the United States in the 2022-2035 timeframe.
[20] 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
[21] Rijkswaterstaat (2019). Routeradar 2019 Straatbeeldmonitor Wegvervoer Routeradar 2019 - Duurzame mobiliteit (rwsduurzamemobiliteit.nl)
[22] https://alternative-fuels-observatory.ec.europa.eu/consumer-portal/electric-vehicle-recharging-prices; data for November 2022
[23] Rijkswaterstaat (2020). Routeradar INNOM Marktontwikkeling Wegvervoer, Publicaties Routeradar - Duurzame mobiliteit (rwsduurzamemobiliteit.nl)
[24] RVO (2021). Handreiking Total cost of ownership (TCO)-berekening voor personenauto's Handreiking TCO-berekening voor personenauto's (rvo.nl)
[25] Transport & Environment (2022). A comparison of car taxation in Europe The good tax guide (transportenvironment.org)
[26] Rijkswaterstaat (2021). Factsheets Q&A discontovoet 2021 Factsheets Q&A discontovoet 2021 | Rapport | RWSeconomie.nl
[27] 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 10: 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 11: 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 10 and Table 11 can be combined with the available PV area in Table 8 to calculate the total costs for the VIPV installations.

1.2.3. Fleet model

In the original approach it was planned that the development of the European EV fleet would be taken from PRIMES-TREMOVE, to be consistent with other European studies. The TREMOVE model and/or results, however, could not be made available to the project team in time to include the projections therein in this first interim report. A rerun or cross-check with TREMOVE data will be added to a later report.

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)[28]. 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[29]. 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 are 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.

[28] : PBL, TNO, CBS & RIVM (2022), Klimaat- en Energieverkenning 2022. PBL Netherlands Environmental Assessment Agency.
[29] https://alternative-fuels-observatory.ec.europa.eu

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.

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.

1.3. Task 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.

1.3.1.1. From individual profiles to neighbourhood demand

The starting point is the collection of demand profiles produced in Task 1.2. These profiles can be extracted from the time series output of the energy flow model (example data shown in Figures 9 -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).

1.3.1.2. Defining neighbourhoods

To compute the total demand at neighbourhood level, we need to multiply each of these average profiles per archetype by the amount 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 amount 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).

1.3.1.3. 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

1.3.2.1. 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[30] 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.

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

2. Simulation Results

The overall simulated results are built by modelling each specific vehicle archetype over a full year. All other results are then built, much like a transportation fleet, from the models of the individual vehicles in that fleet. On top of that we lay a model of the grid to gain a more complete understanding of the wholistic picture. We will start with the results of the vehicle level modelling.

2.1.1. Results Energy Flow Model

Energy flows over the year

As described in paragraph 1.1.5.2 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.

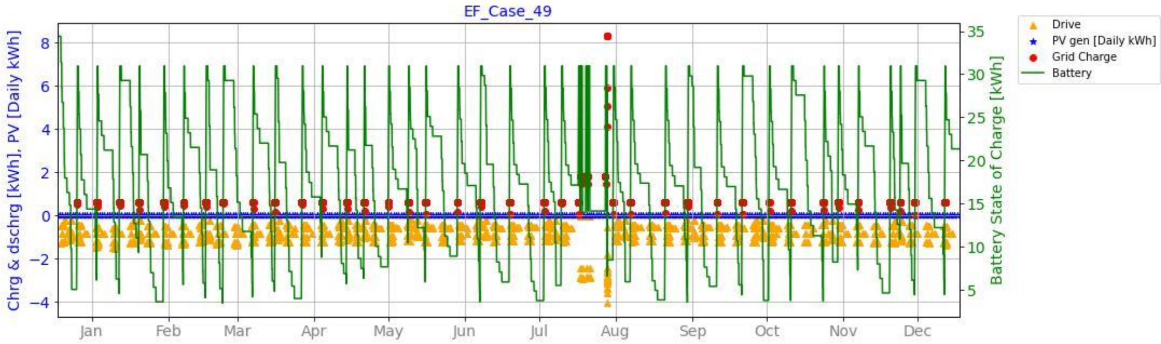


Figure 9: LP12, small passenger car, with no PV - Rresults in 46 charging moments in the year (red circles) using charging strategy A.

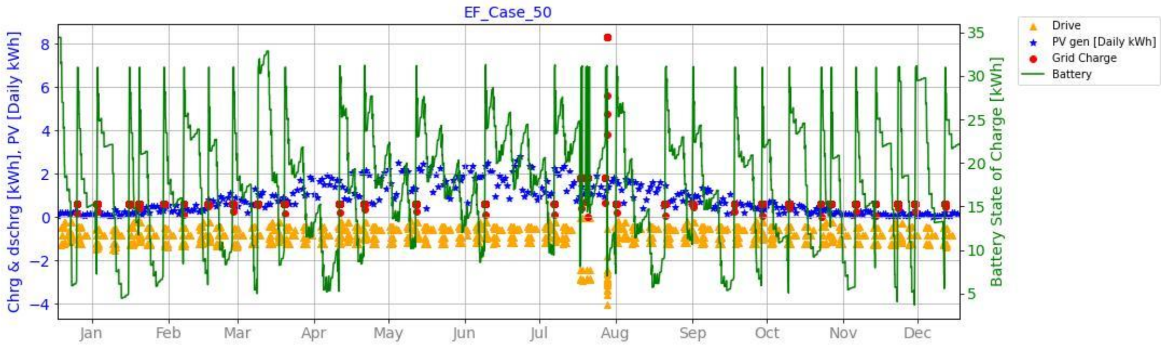


Figure 10: LP12, small passenger car, with PV on sun facing surfaces – Results in , far less charging moments, especially in summer. In total 36 charging moments in the year using charging strategy A.

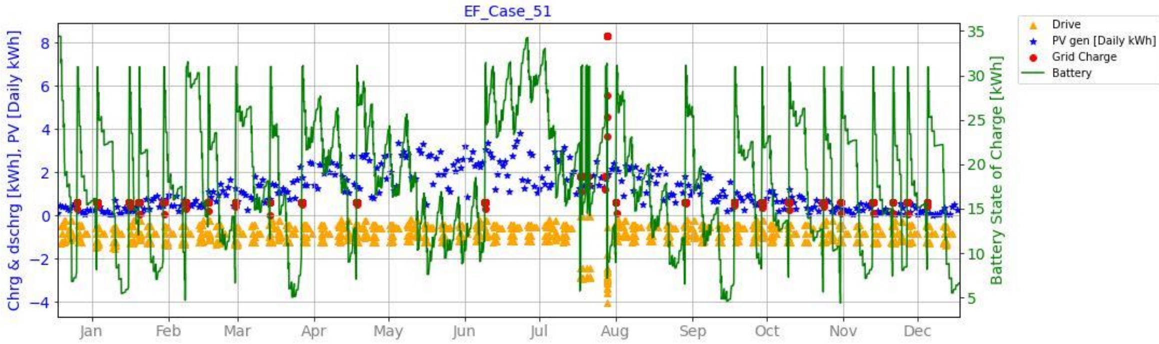


Figure 11: LP12, small passenger car, with PV on all surfaces - . The number of charging moments is further reduced to 31 for the year.

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 r 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.

This is done for all archetypes based on the energy consumption of the different archetypes in 2023 configuration.

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.

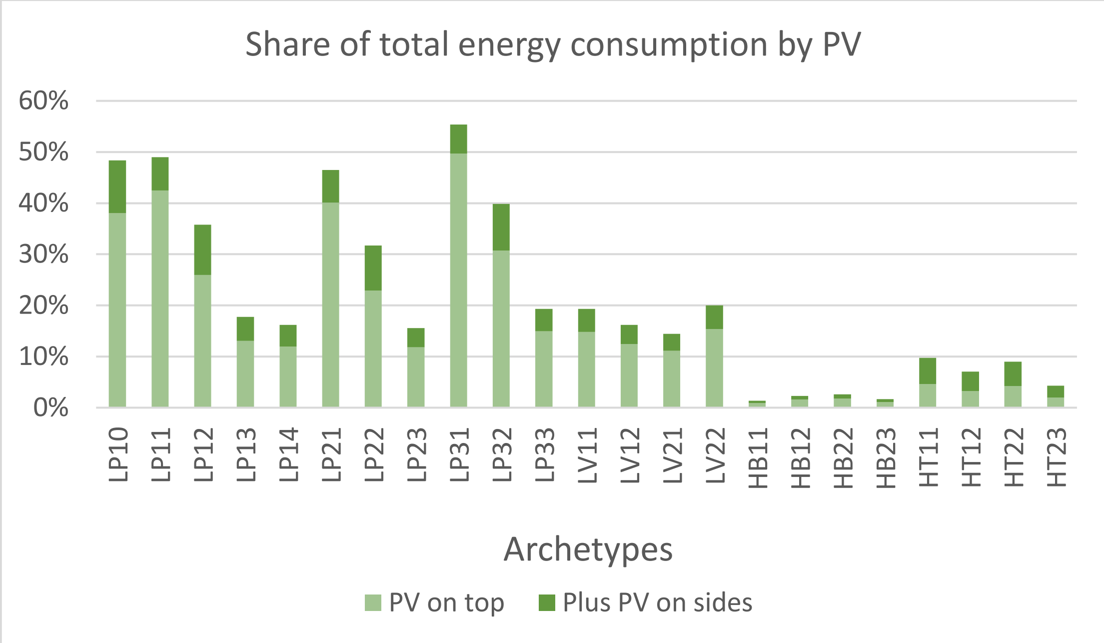


Figure 12: Share of total energy consumption provided by PV of each archetype (Amsterdam)

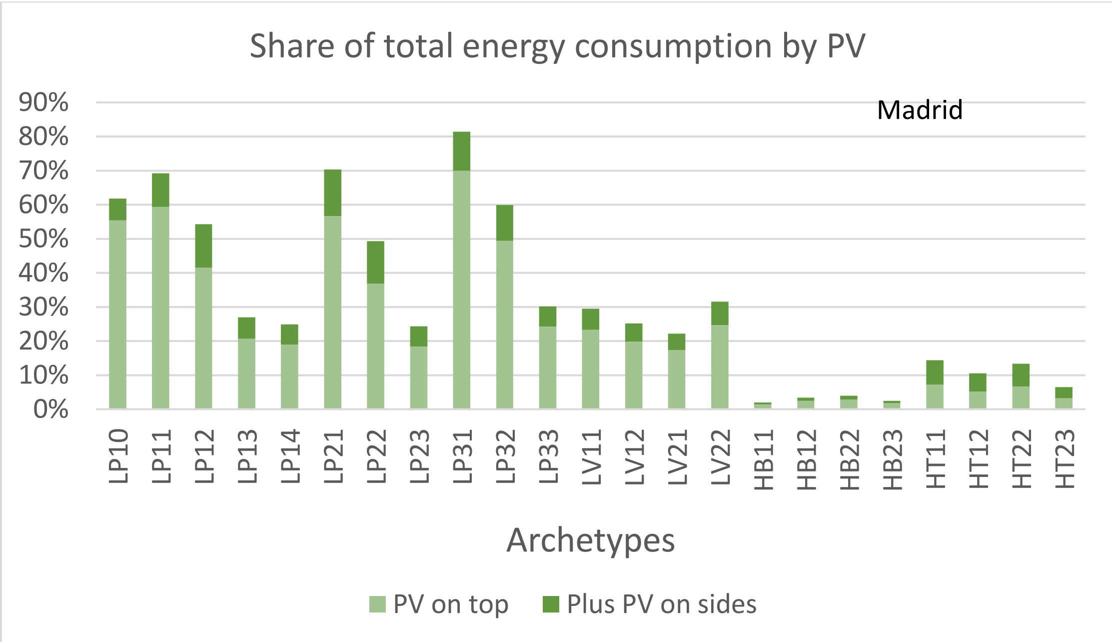


Figure 13: Share of total energy consumption provided by PV of each archetype (Madrid)

2.2. Task 1.2 Energy efficiency impacts on EU fleet composition

2.2.1. 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 12 and Table 13 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 12 and Table 13 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 12: 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 13: 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

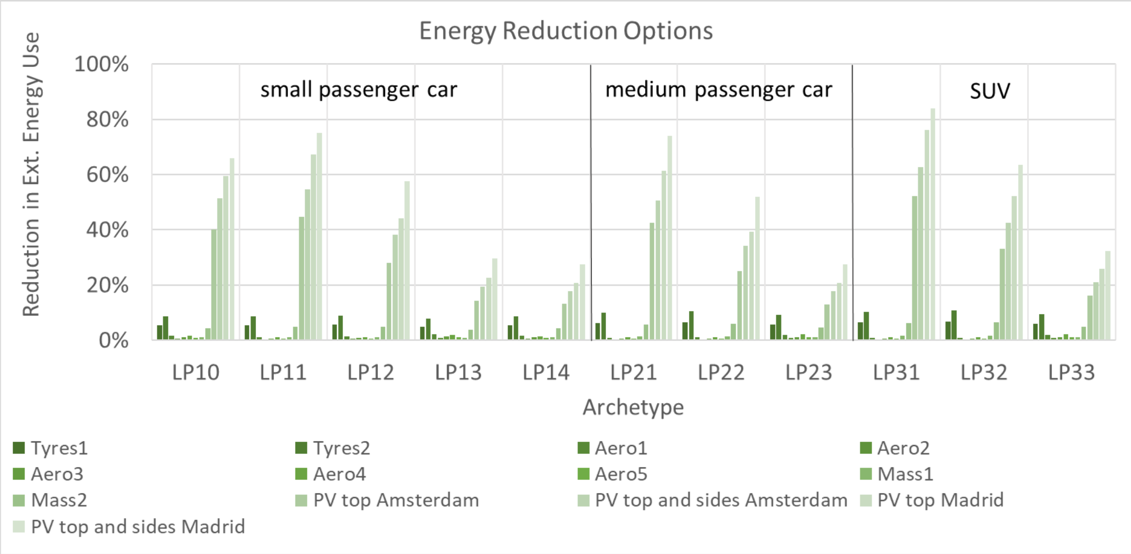


Figure 14: Reduction in external energy consumption for passenger cars relative to the energy consumption of the Amsterdam baseline vehicle.

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 in 1.1.1.3 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 14: 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

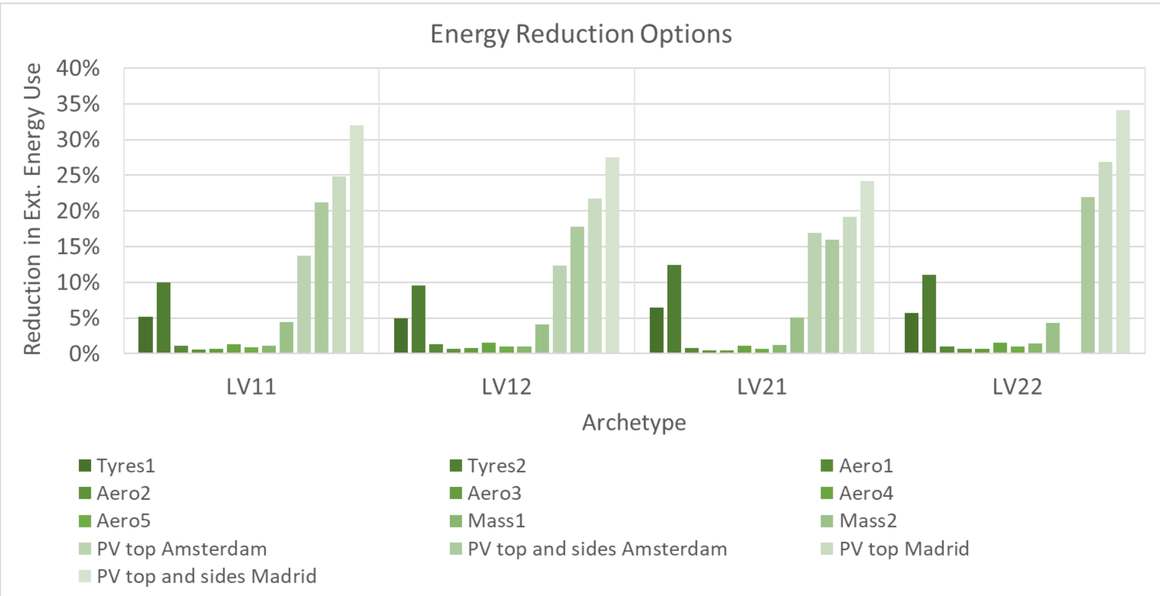


Figure 15: Reduction in external energy consumption for vans relative to the energy consumption of the Amsterdam baseline vehicle..

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 15: 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

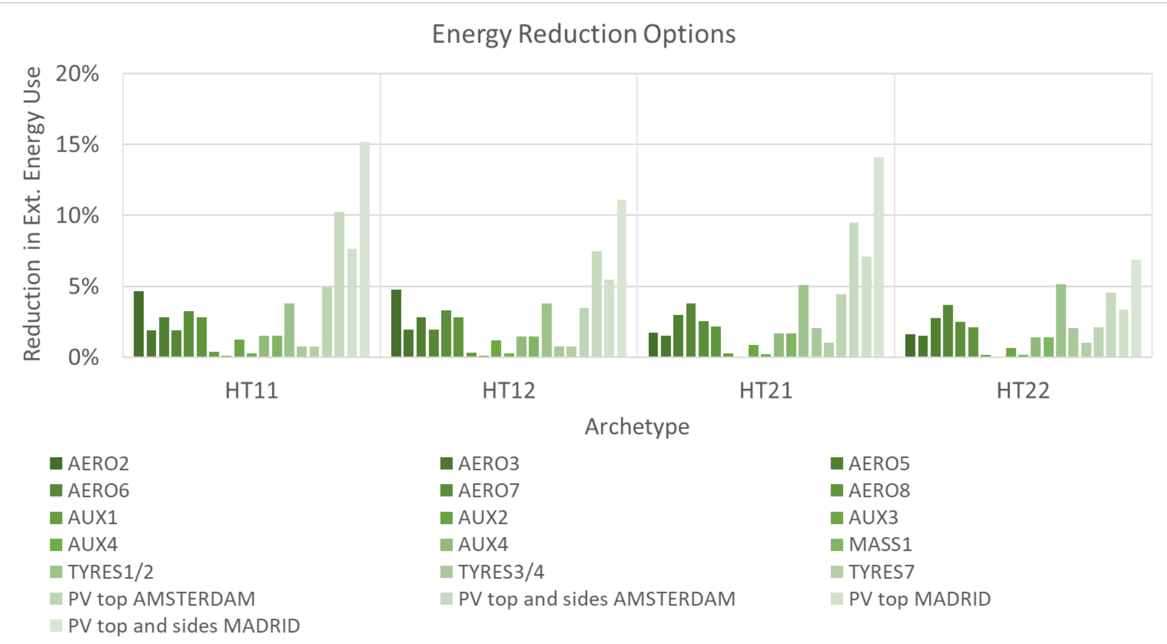


Figure 16 Reduction in external energy consumption for trucks relative to the energy consumption of the Amsterdam baseline vehicle.

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.

Table 16: 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												

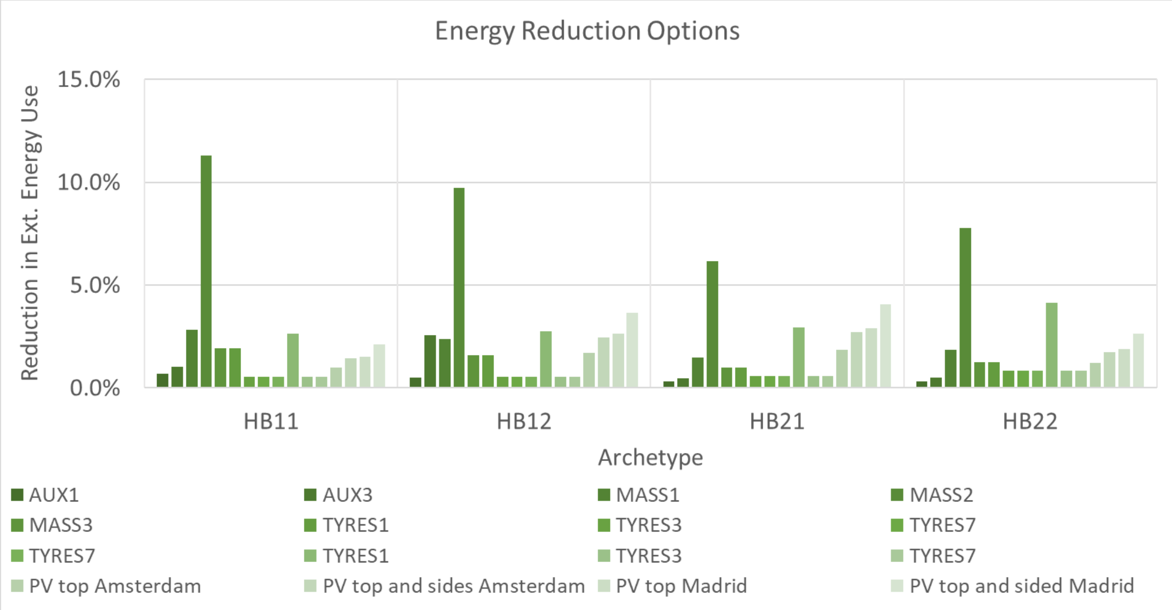


Figure 17: Reduction in external energy consumption for busses relative to the energy consumption of the Amsterdam baseline vehicle.

2.2.2. 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 D).

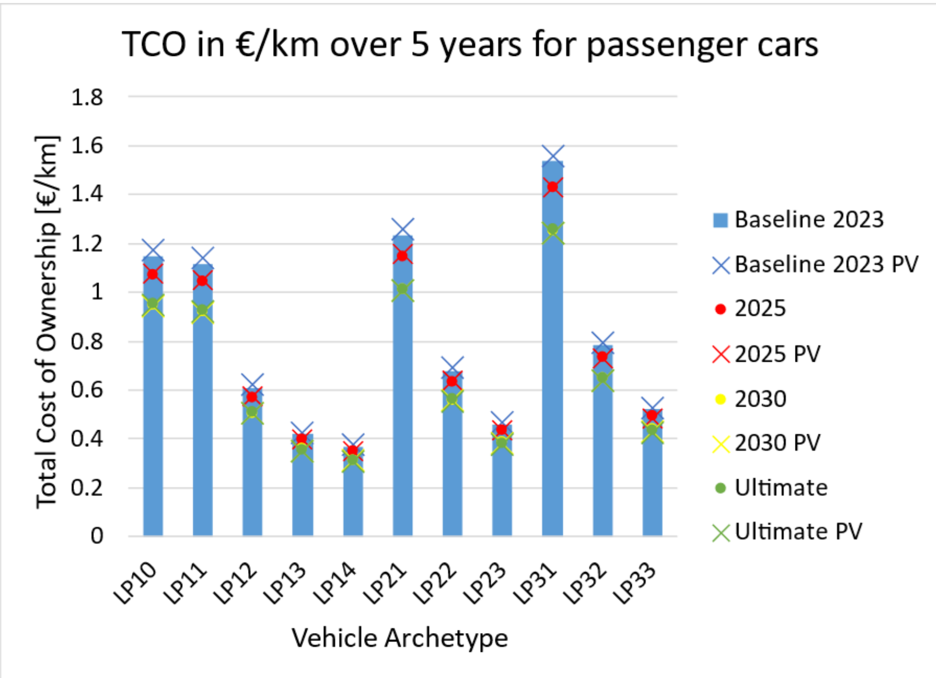


Figure 18. Total cost of ownership in euros per kilometre for different vehicle passenger car archetypes and different scenarios based on their efficiency improvements for an ownership period of 5 years

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 D 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.

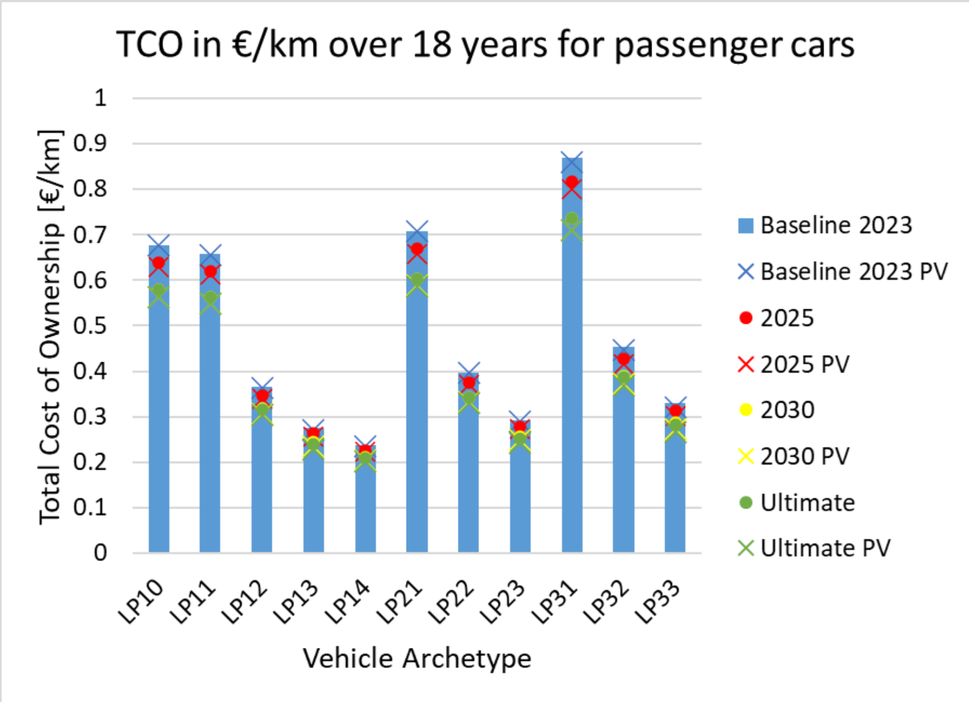


Figure 19. Total cost of ownership in euros per kilometre for different passenger car archetypes and different scenarios based on their efficiency improvements for an ownership of 18 years

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, for instance, 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 same difference 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.

2.2.3. Grid electricity consumption

The results of paragraph 2.2.1 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.

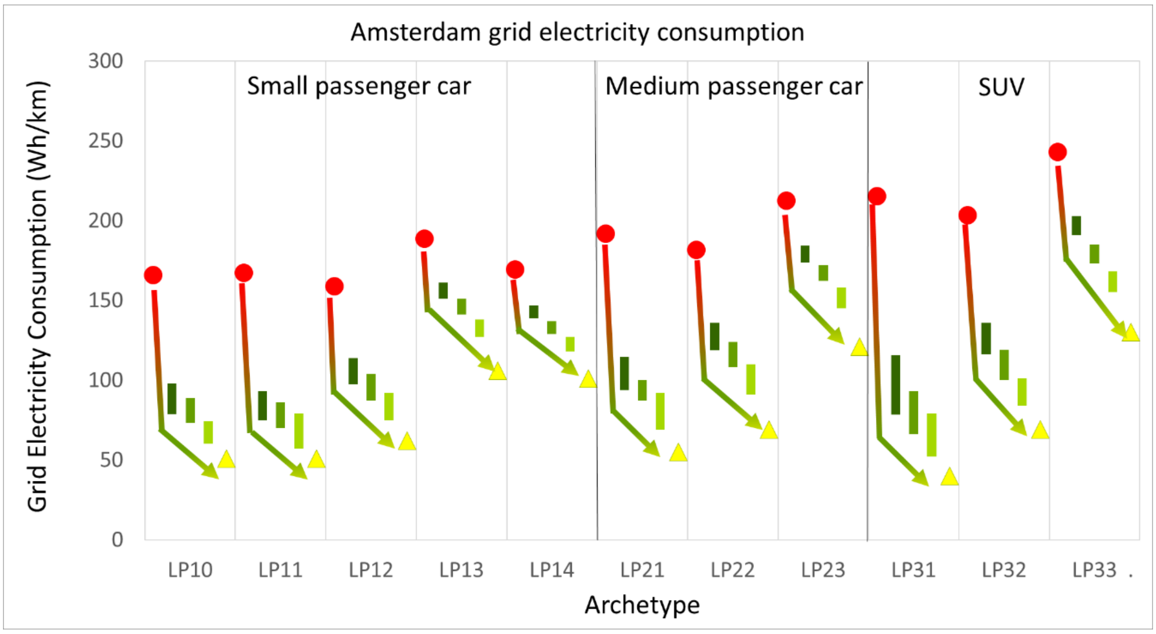


Figure 20: Amsterdam grid electricity consumption for an electric passenger car

- ***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 12 and Table 13. 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 12 and Table 13 . 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 12 and Table 13, an additional reduction can be achieved, but those are not viable from a cost perspective.

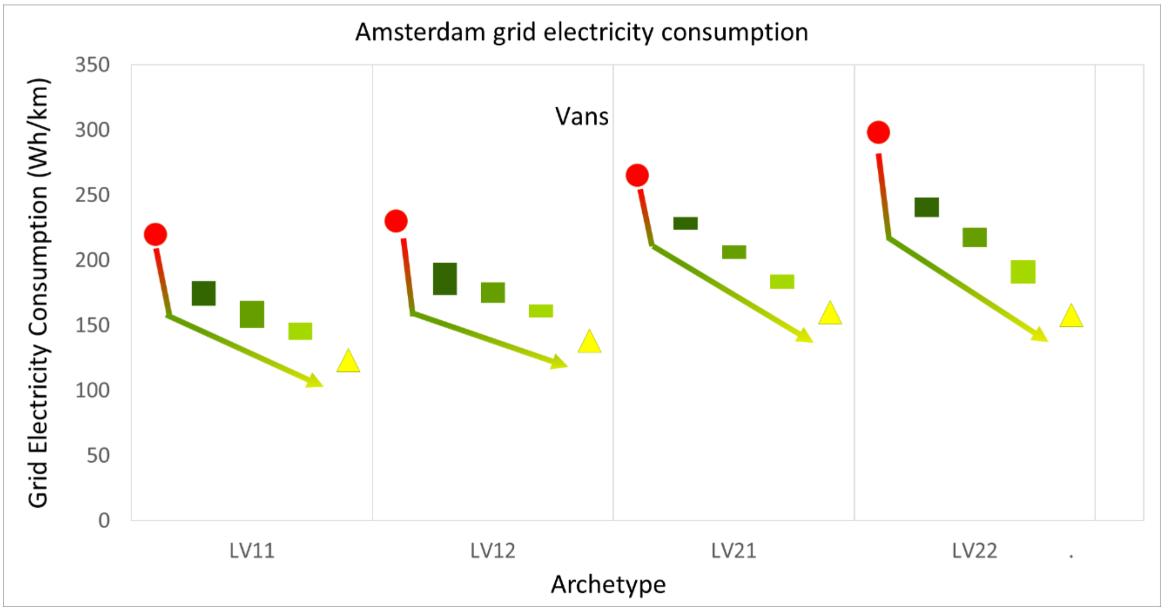


Figure 21: Amsterdam grid electricity consumption for an electric van

- ***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 12 and Table 13. Arrows are a guide to the eye.

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%. Adding the cost effective energy reduction options results in an additional reduction for both 2025 and 2030.

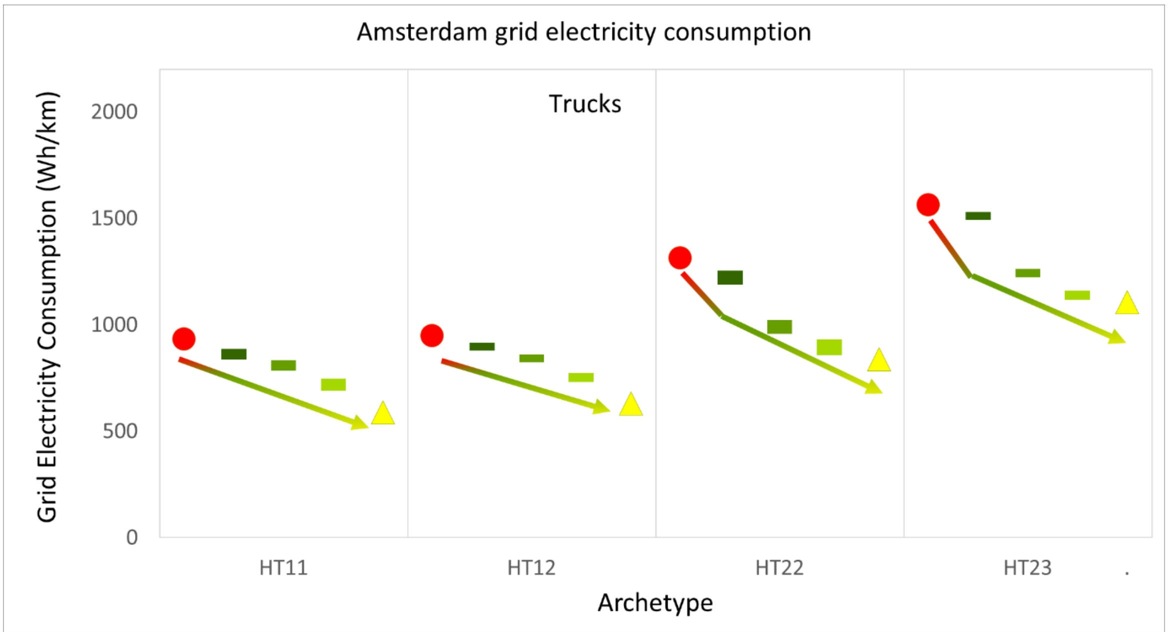


Figure 22: Amsterdam grid electricity consumption for an electric truck

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 12 and Table 13. Arrows are a guide to the eye.

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. Similar results are obtained for buses (Figure 23).

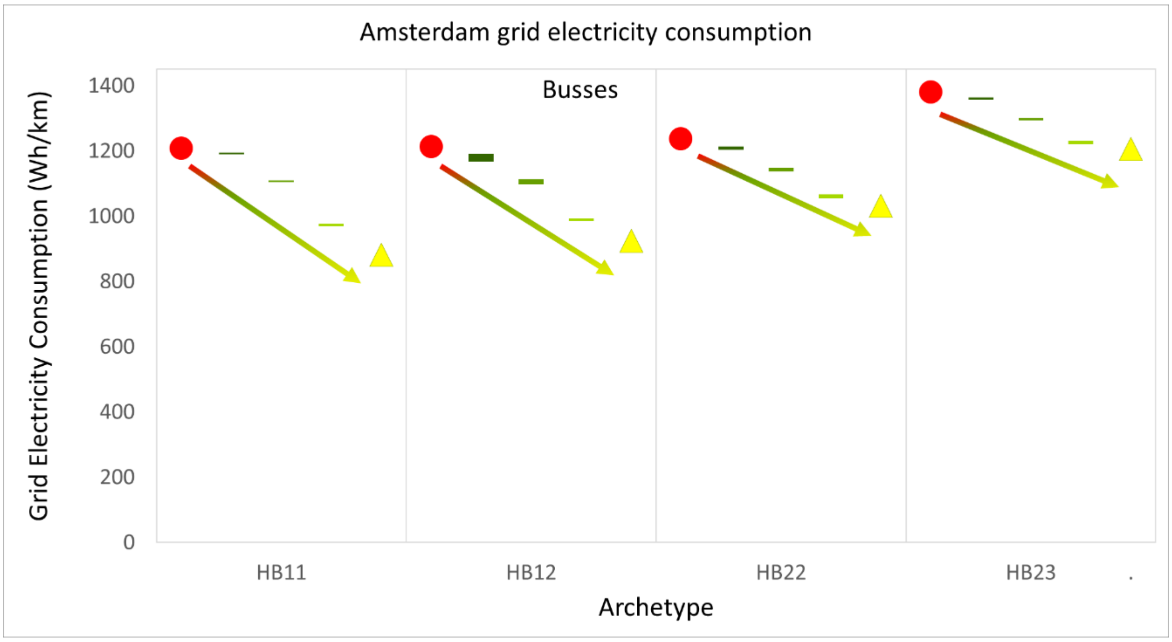


Figure 23: Amsterdam grid electricity consumption an electric bus

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 12 and Table 13. Arrows are a guide to the eye.

2.2.4. 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.

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.

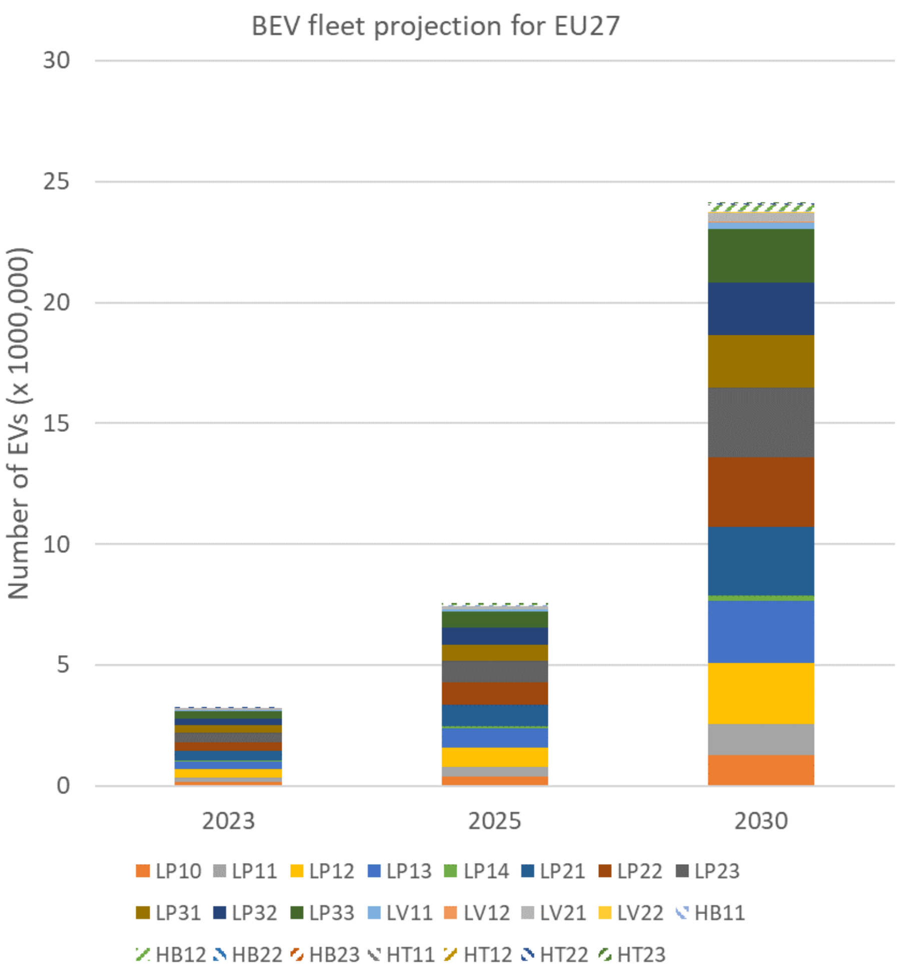


Figure 24: EU27 EV fleet in 2023 and projection for 2025 and 2030, broken down in SolarMoves archetypes

The electrification rate in the graph corresponds to the following values, see Table 17.

Table 17: 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.

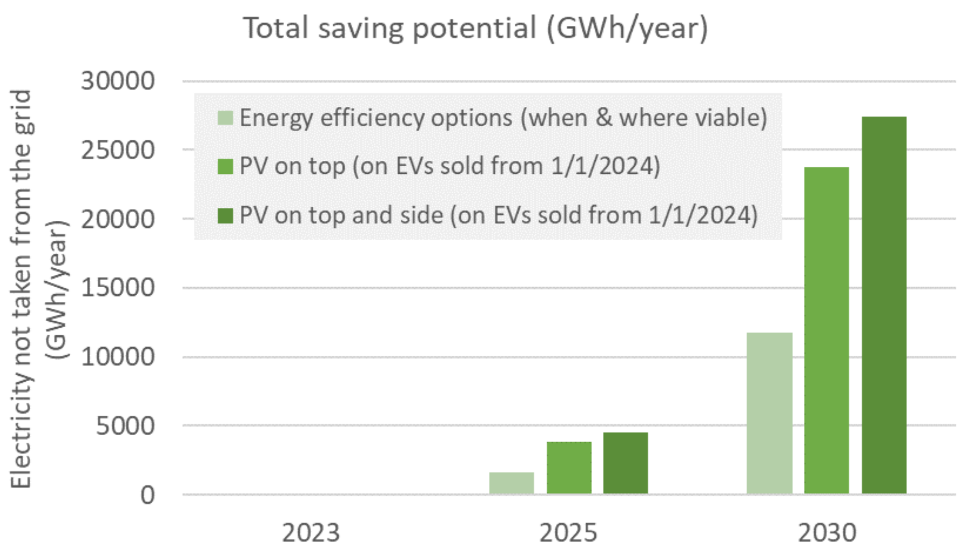


Figure 25: Potentially avoided grid electricity consumption resulting from reduced energy consumption options and VIPV, for the projected EV fleet, EU27. Baseline=2023 vehicle efficiency & no VIPV. Additional fleet only = only newly sold vehicles from 1/1/2024 onwards.

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.

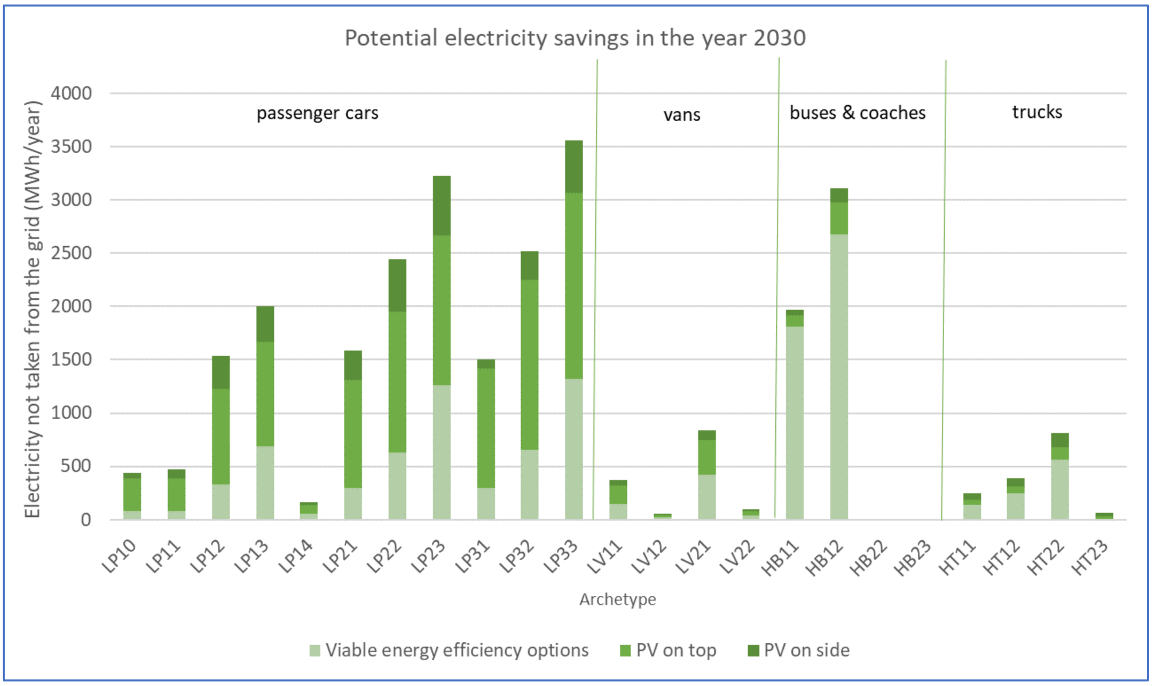


Figure 26: Contribution of the different vehicle archetypes to the potential electricity savings in 2030 for the vehicle archetypes.

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 18.

Table 18: 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 18 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.

2.3. Task 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

In order to quantify the impact of vehicle efficiency improvements, including VIPV, on the grid and infrastructure, we consider two different locality levels. The first is the neighbourhood level and the impact on local demand. In future analysis, not included in this report, the results will be scaled to regional and/or national grid level as well.

2.3.1. 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 (as defined in Section 1.1.5.3).

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.

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 Section 2.2.3 at the vehicle and full EU fleet level.

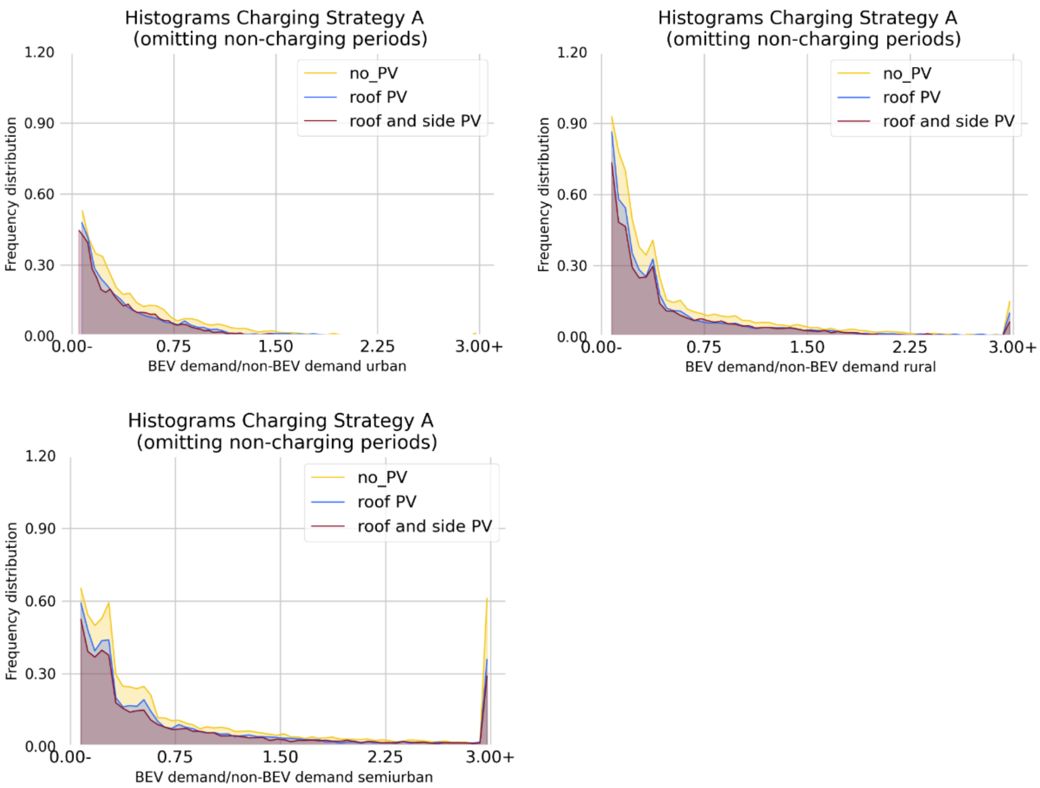


Figure 27: BEV/non-BEV demand frequency distribution for the three neighbourhoods (urban (top left), rural (top right), semiurban (bottom left)) in The Netherlands and Charging Strategy A, with the first bin removed for visibility reasons.

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).

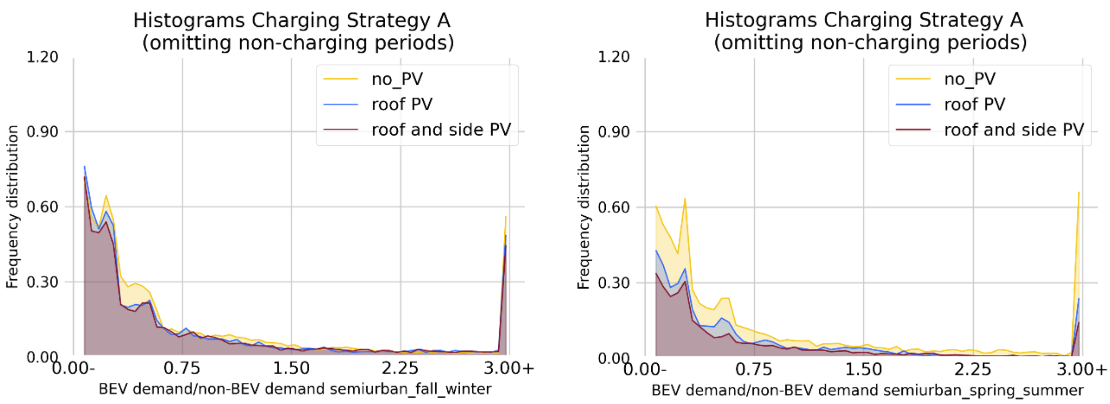


Figure 28: Seasonal comparison of BEV/non-BEV demand frequency distribution for the semiurban neighbourhood in The Netherlands and Charging Strategy A, with the first bin removed for visibility reasons. The comparison is for Fall-Winter (left) and Spring-Summer (right)

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 Section 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[31]

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.

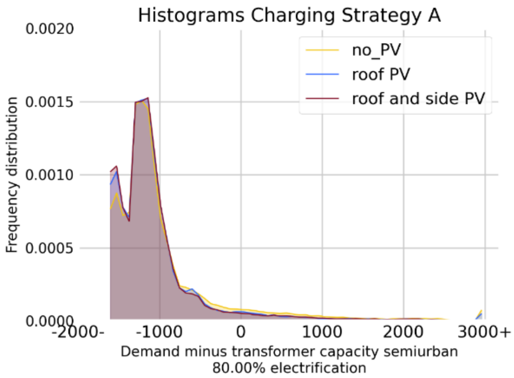


Figure 29: Demand minus transformer capacity frequency distribution for the urban neighbourhood in The Netherlands and Charging Strategy A, at 80% electrification.

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 the semi-urban 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 Section 1.3.1.2), 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

[31] 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.

neighbourhood versus 3.52 kVA/household in the rural neighbourhood, as detailed in Section 1.3.2.1).

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.

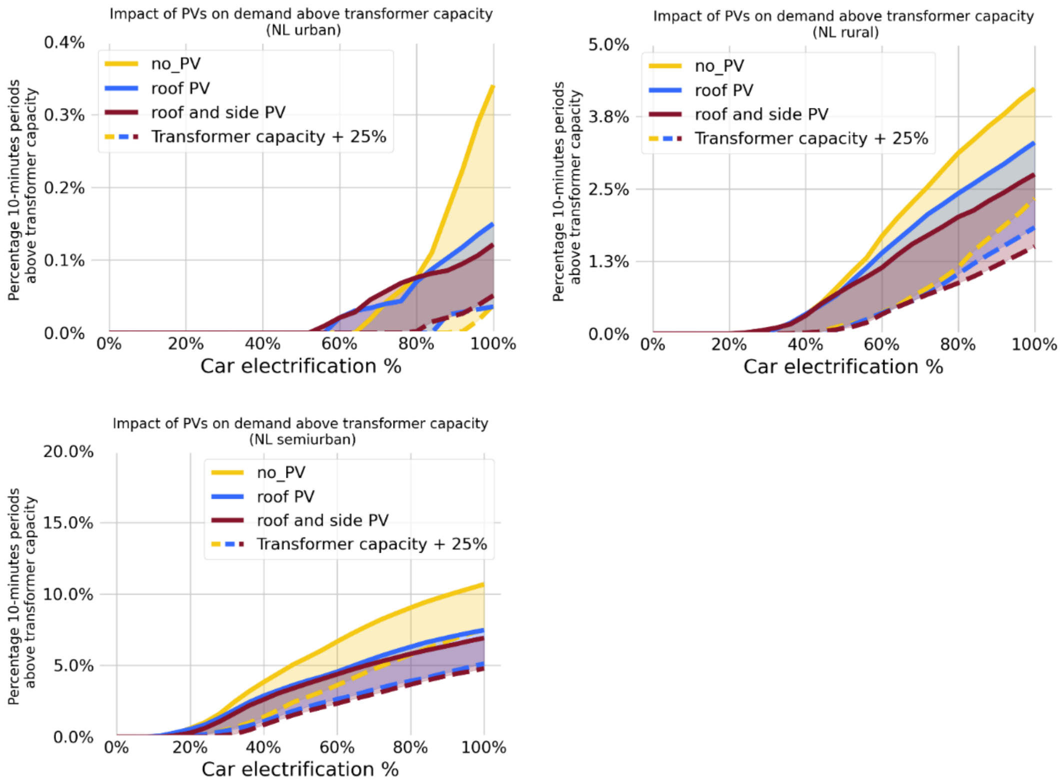


Figure 30: Percentage of time where the demand is above the transformer capacity as function of the neighbourhood vehicle electrification level for the neighbourhood in the Netherlands ((urban (top left), rural (top right), semiurban (bottom left)).

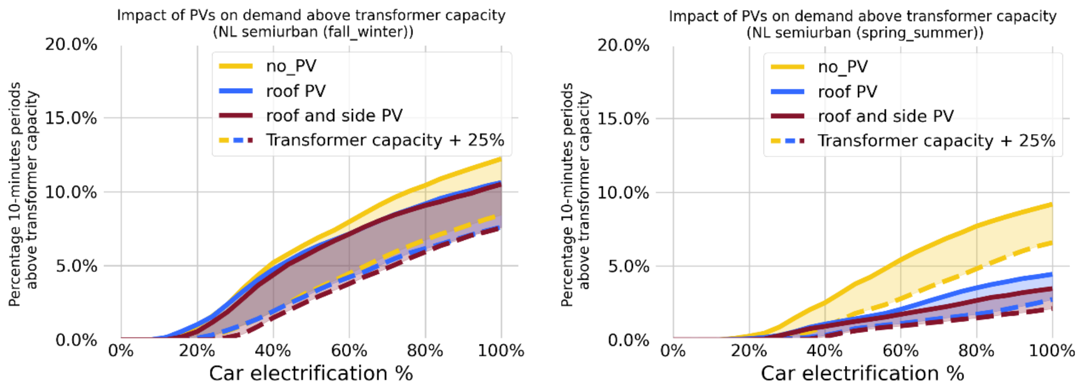


Figure 31 Seasonal comparison of the percentage of time where the demand is above the transformer capacity as function of the neighbourhood vehicle electrification level for the urban neighbourhood in the Netherlands, with fall-winter on the left and spring-summer on the right.

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.

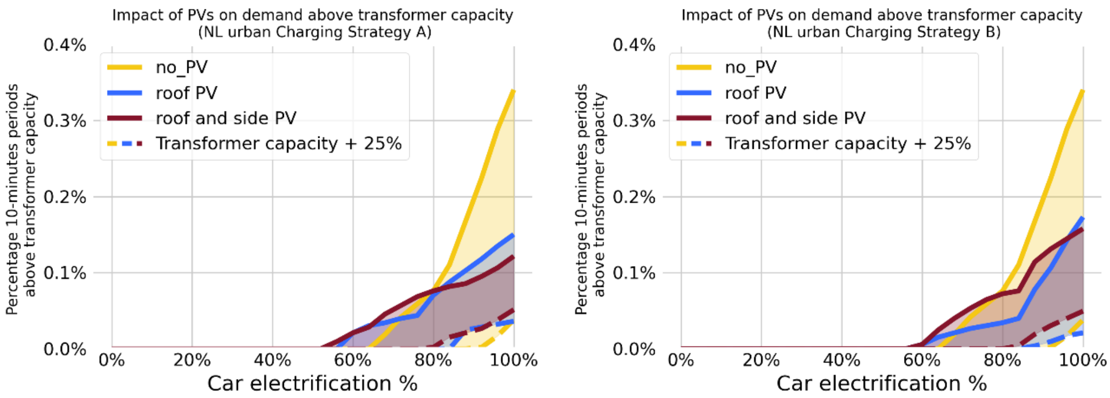


Figure 32 Yearly occurrences above transformer capacity, comparison between charging strategies A and B.

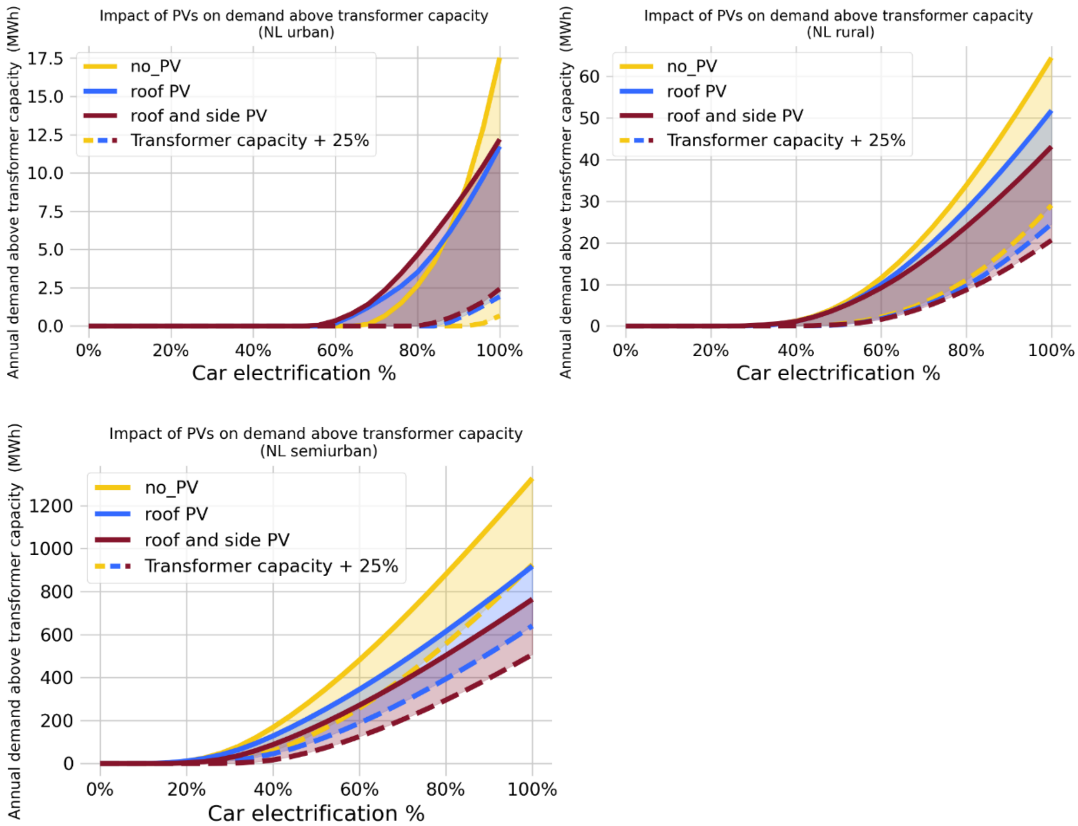


Figure 33 Annual demand above transformer capacity as a function of car electrification for the Dutch cases (urban (top left), rural (top right), semiurban (bottom left)).

3. 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.

3.1. 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.

3.2. 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.

3.3. 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.

3.4. 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 enegy 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.

3.5. 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.

3.6. 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 these 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, Task 2 of this work 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.

Appendices

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 3 shows the

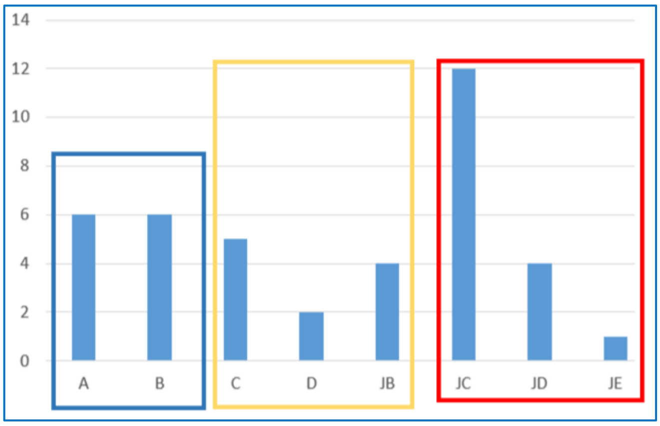


Figure 34: top 40 passenger EV sales and their division among the categories small (blue), medium (yellow) and SUV (red)

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 3 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 colored 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 4 shows the average frontal area of the different segments, which confirms that the small SUV's fit well in the medium category.

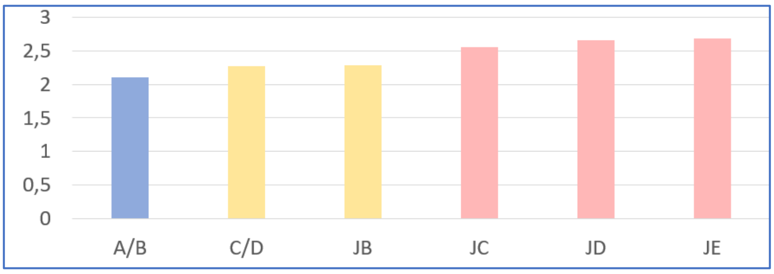


Figure 35: Frontal area (m²) of the different categories compared

The resulting top 10's are shown in table 2.

Table 19: 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-flor 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 regid 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 [32] and [33].

[32] European Alternative Fuels Observatory (EAFO), https://alternative-fuels-observatory.ec.europa.eu; detailed data from personal exchange with FIER Automotive
[33] 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 20: Description of passenger vehicle archetypes, including annual mileage and distribution over road types.

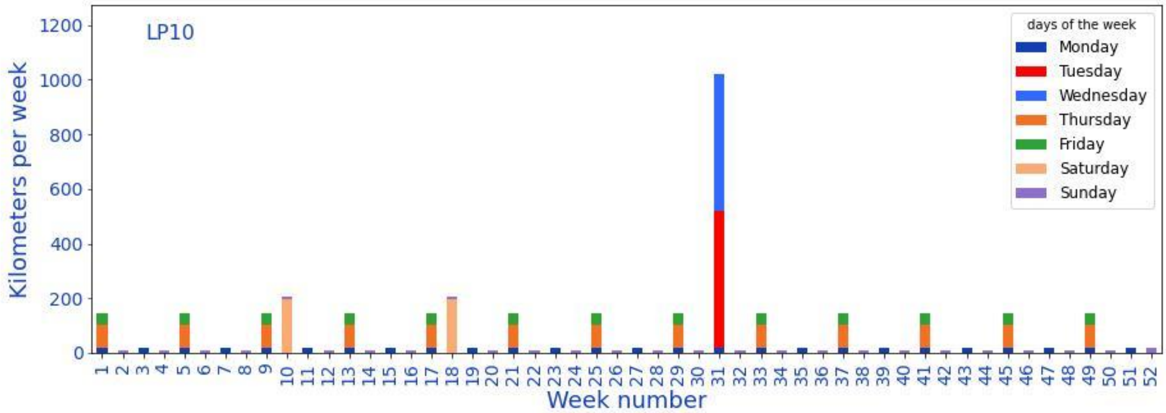
Vehicle type	Vehicle class and type	Use pattern	Description	Annual mileage (km)	Urban	Rural	Motorway
LP10	Small passenger car	Occasional use	Cars that are driven a few times a week	3795	21%	42%	37%
LP11	Small passenger car	Daily urban commute	Cars that are driven mostly in urban areas on a daily basis	3894	70%	10%	20%
LP12	Small passenger car	Daily 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%

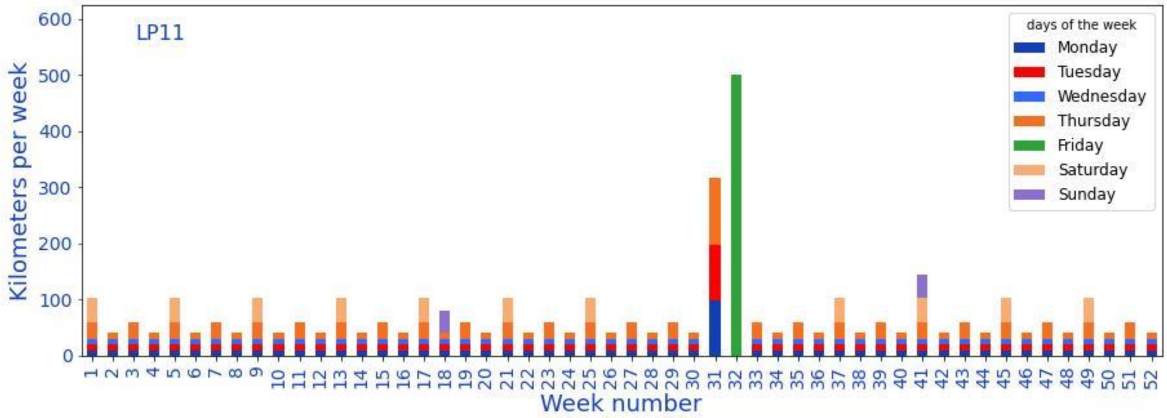
Table 21: trip definitions for passenger cars per vehicle archetype.

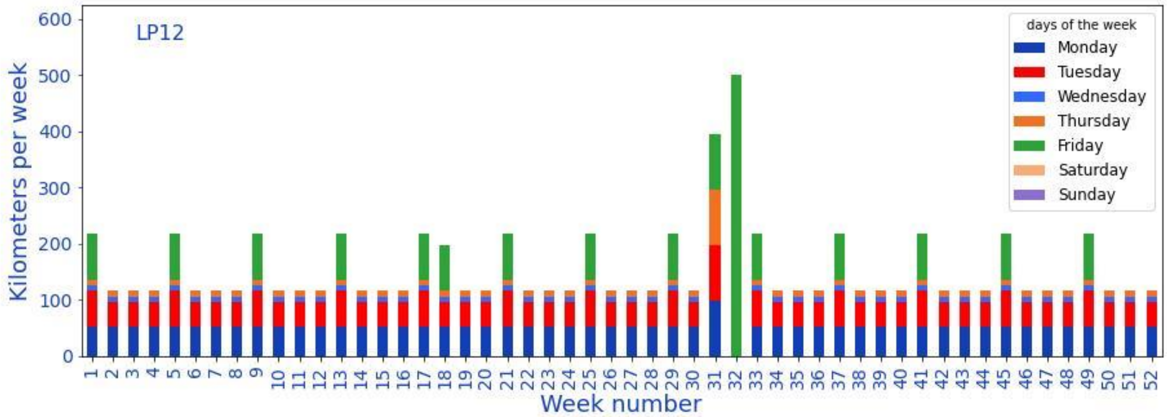
	LP10			LP11			LP12			LP13			LP14		
Trip Type	**Days**	**Time**	**Total in the year**	**Days**	**Time**	**Total in the year**	**Days**	**Time**	**Total in the year**	**Days**	**Time**	**Total in the year**	**Days**	**Time**	**Total in the year**
5 km	Mondays	11:00	52	Mondays – Thursdays (excl. holidays)	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

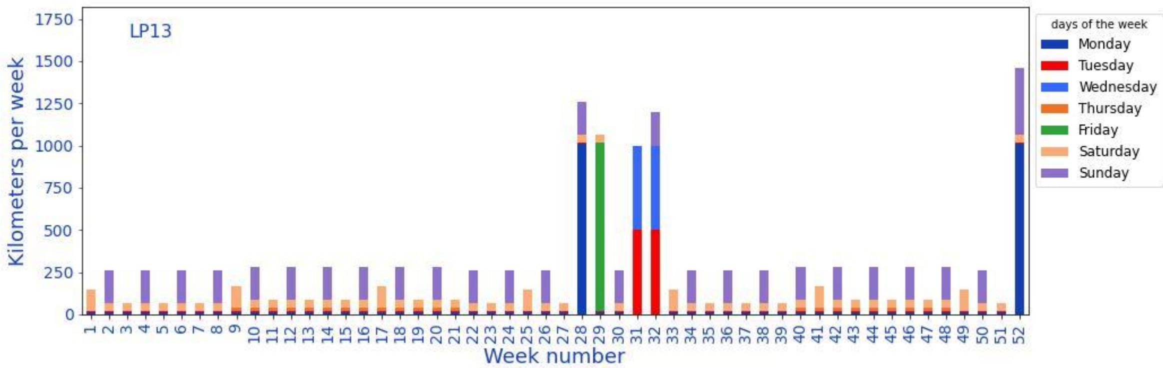
10 km	Mondays	12:00	52	Thursdays	20:00	52	Thursdays	20:00	32	Thursdays (January – June + September – November)	20:00	32	Monday-Friday (excl. 2 week summer)	14:00	250
20 km	Every other Thursday	14:00	26	1st Saturday of month + 2 random Saturdays	10:00	14	Mondays, Wednesdays Tuesdays, Thursdays	09:00 17:00	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			

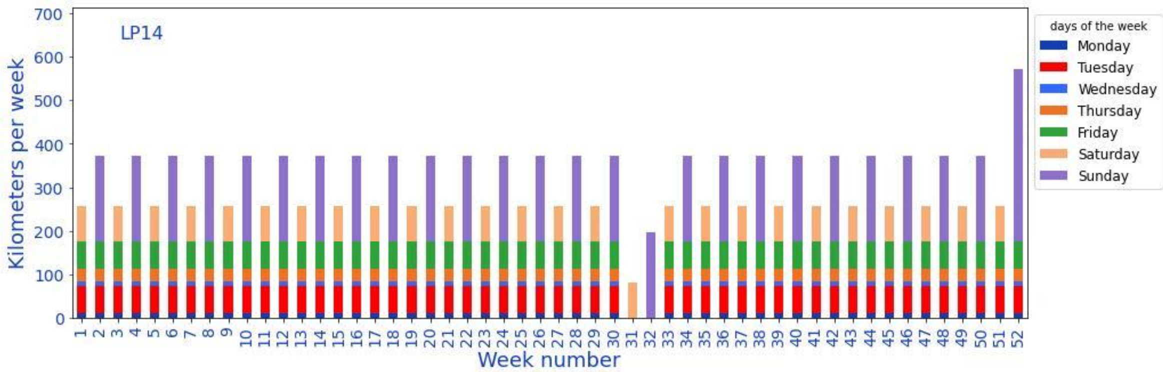
Weekly kilometre profile charts for each archetype: LP10 – LP14











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 22 and Table 23.

Table 22: Description of medium passenger vehicle archetypes, including annual mileage and distribution over road types.

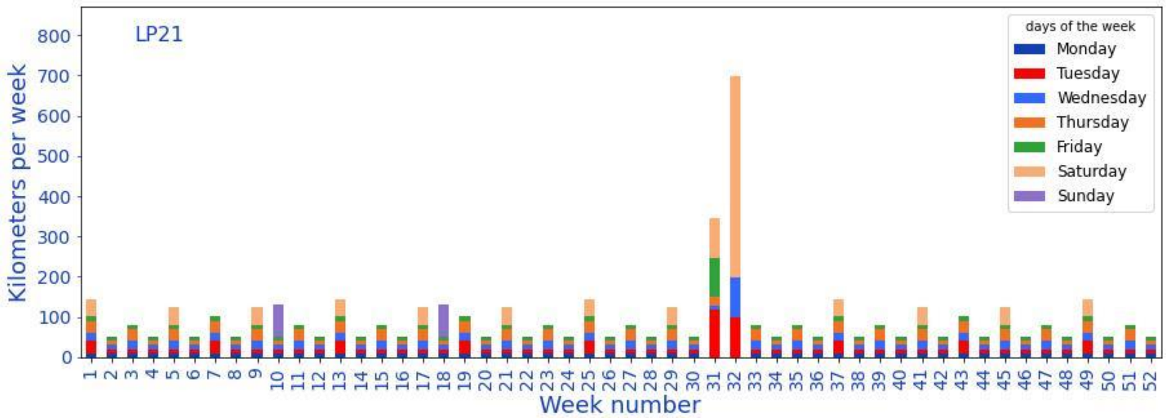
Vehicle type	Definition	Description	*Annual mileage (km)*	Urban	Rural	Motor way
LP21	Medium Passenger car, daily urban distribution	"Cars that are driven mostly in urban areas on a daily basis".	5164	70%	10%	20%
LP22	Medium Passenger car, daily periurban distribution	"Cars of people that live outside 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%

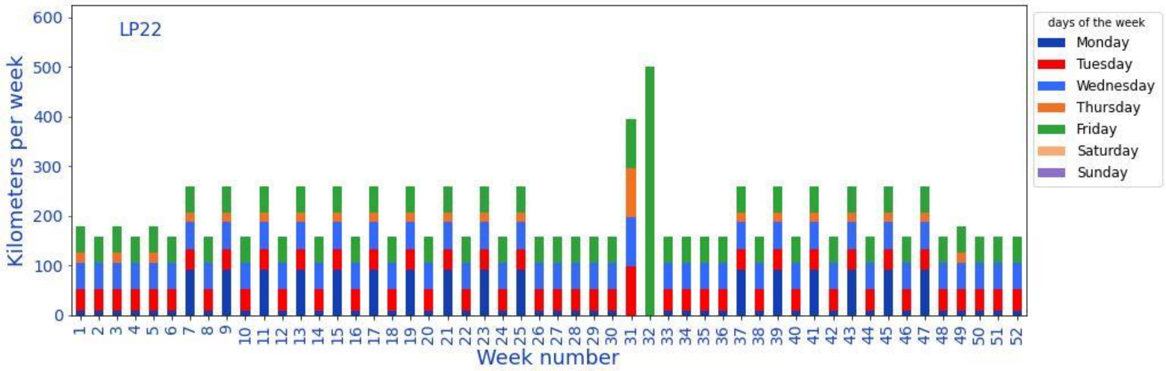
Table 23: trip definitions for medium passenger cars per vehicle archetype.

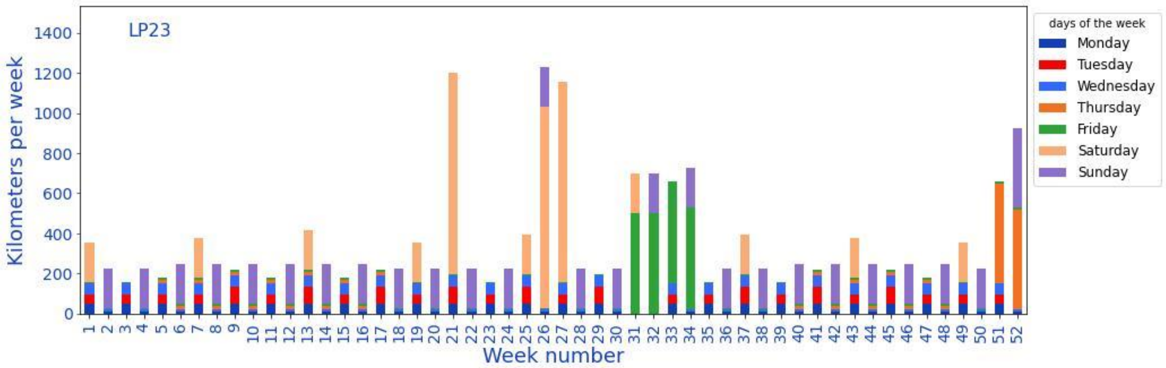
	LP21			**LP22**			**LP23**		
Trip Type	**Days**	**Time**	**Total in the year**	**Days**	**Time**	**Total in the year**	**Days**	**Time**	**Total in the year**
5 km	Mondays – Fridays (excl. holidays) Mondays, Wednesdays (excl. holidays)	19:00 21:00	250 100	Mondays – Fridays (excl. holidays) Wednesdays (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

Weekly kilometre profile charts for each archetype: LP21 – LP23







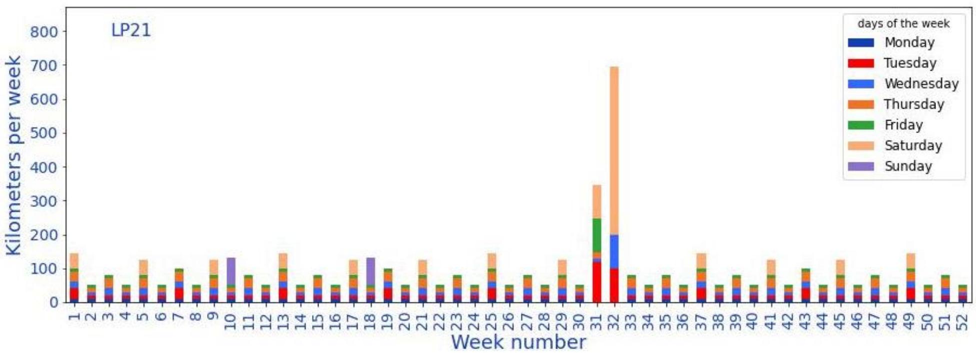


Figure 36: LP21 Annual driving profile, showing total weekly kilometres by day.

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 22 and Table 23.

Table 24: Description of SUV vehicle archetypes, including annual mileage and distribution over road types.

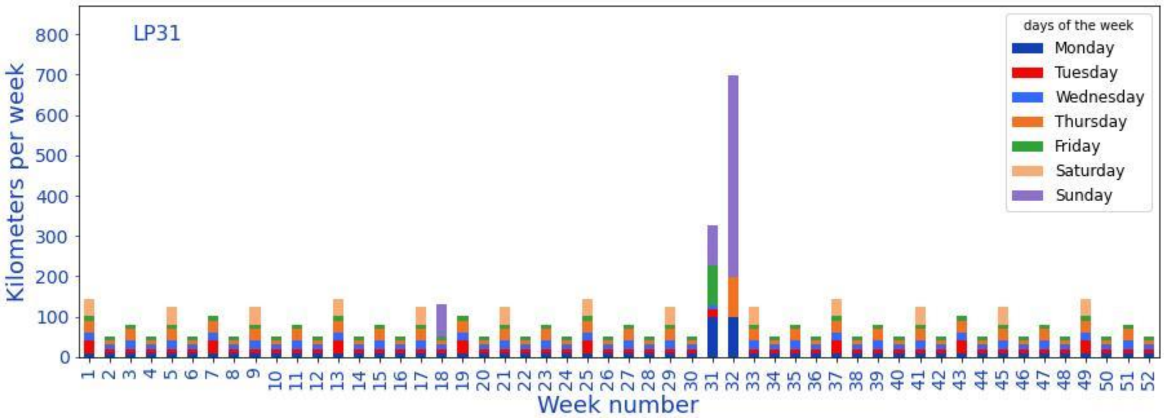
Vehicle type	Definition	Description	*Annual mileage (km)*	Urban	Rural	Motor way
LP31	SUV daily urban distribution	"Cars that are driven mostly in urban areas on a daily basis".	5016	70%	10%	20%

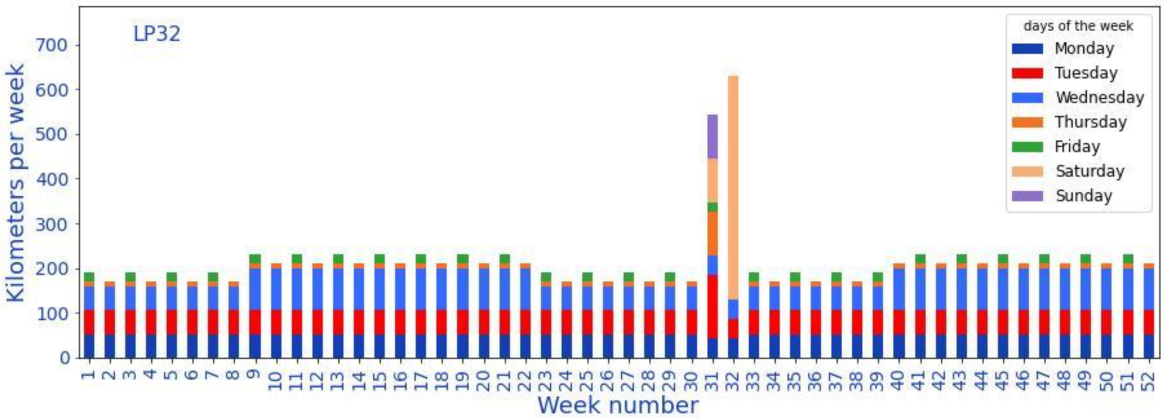
LP32	SUV daily periurban distribution	"Cars of people that live outside of the city and or use their car on a daily basis to commute to rural areas".	11230	20%	70%	10%
LP33	SUV long-distance highway travel	"Cars that commute most of their mileages on motorways for long-distance travel, due to business and holidays".	20619	20%	10%	70%

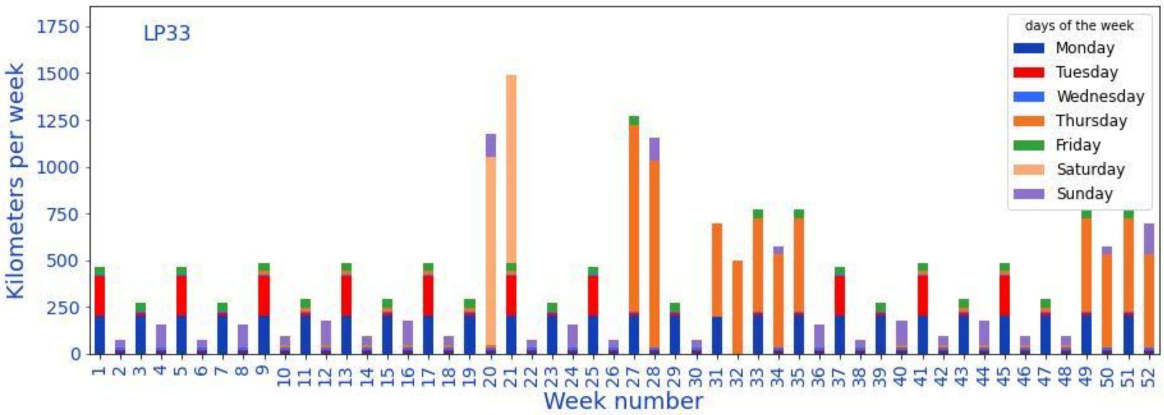
Table 25: trip definitions for SUV's per vehicle archetype.

	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

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 26 and Table 27.

Table 26: 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%

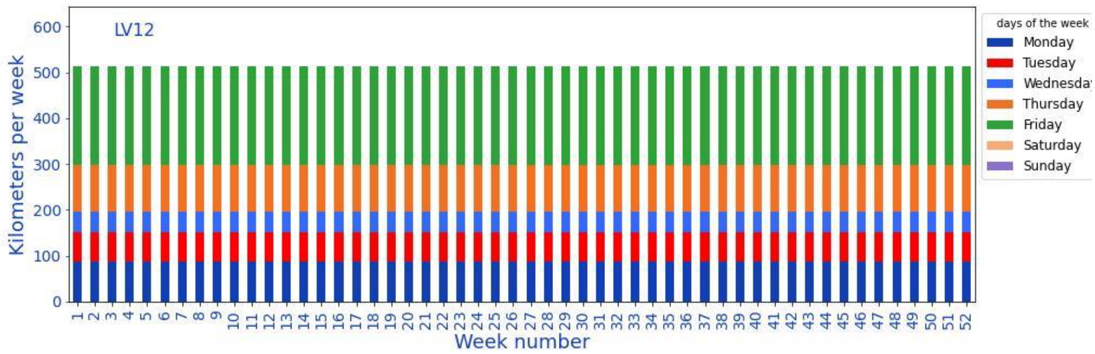
LV12	Small van, regional distribution	26752	20%	40%	30%
LV21	Large van, local distribution	29464	40%	20%	30%
LV22	Large van, regional distribution	23519	20%	40%	30%

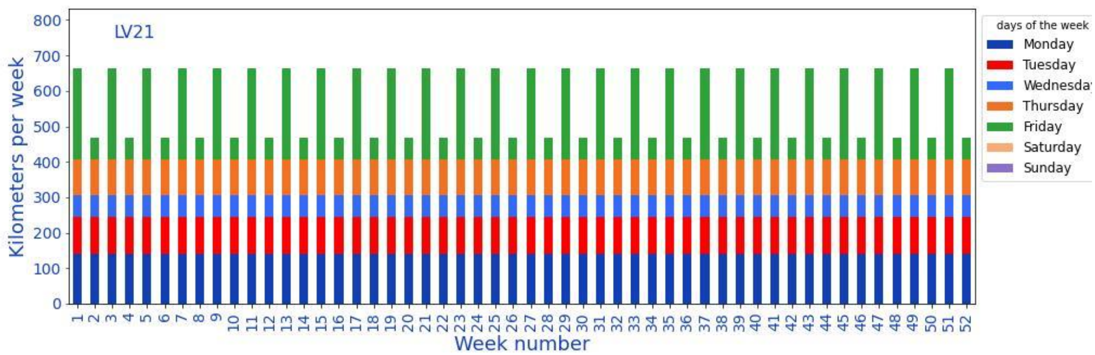
Table 27: trip definitions for vans per vehicle archetype.

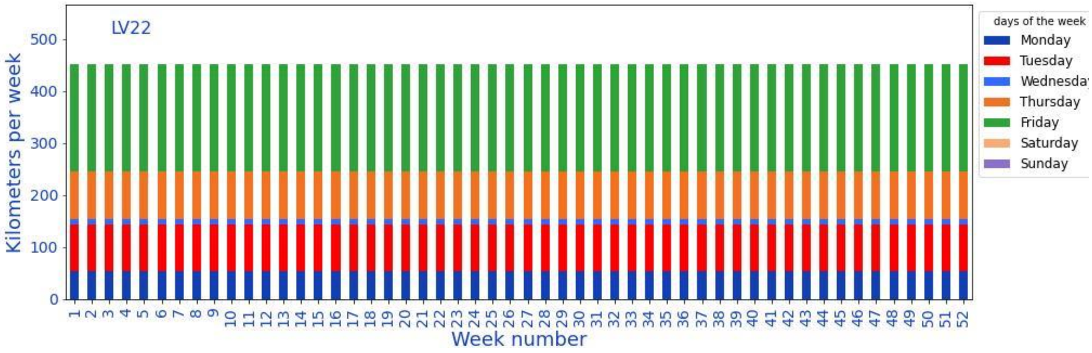
	LV11			**LV12**			**LV21**			**LV22**		
Trip Type	**Days**	**Time**	**Total in the year**	**Days**	**Time**	**Total in the year**	**Days**	**Time**	**Total in the year**	**Days**	**Time**	**Total in the year**
5 km	Mon–Thur excl. holidays Fri excl. holidays	9AM 10AM 11AM 3PM 4PM 10AM 11AM 3PM 4PM	1040 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

Weekly kilometre profile charts for each archetype: LV12, LV13, LV21 & LV22






LV22
Kilometers per week
0
100
200
300
400
500
Week number
days of the week
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday

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 28: Description of truck vehicle archetypes, including annual mileage and distribution over road types.

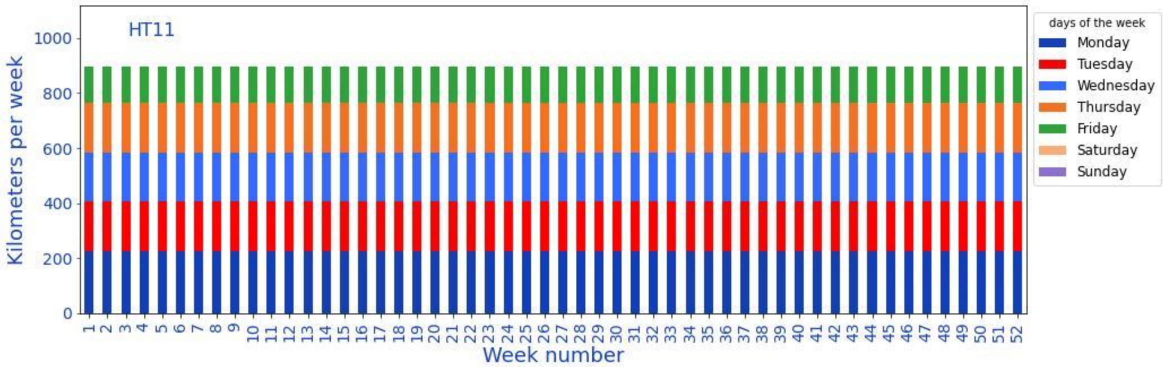
Vehicle type	Definition	*Annual mileage (km)*	Urban	Rural	Motor way
HT11	urban distribution	46523	66%	15%	19%
HT12 & HT22	Tractor and Rigid – regional distribution	80166	43%	31%	26%
HT13	Tractor – long-haul freight transport	141336	26%	24%	50%

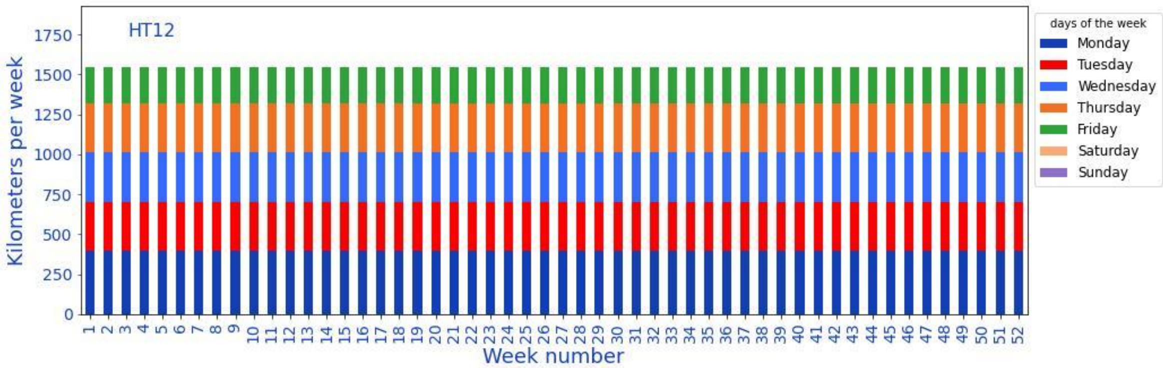
Table 29: trip definitions for trucks per vehicle archetype.

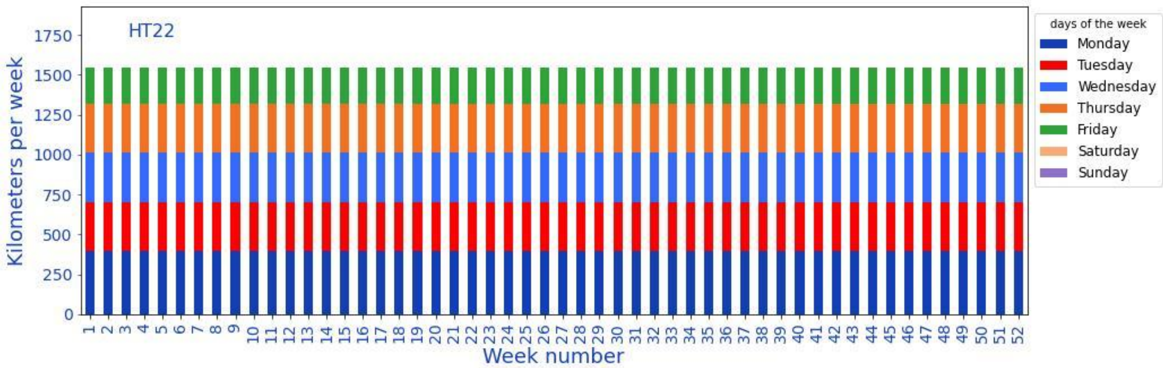
	THT11			**HT12 & HT22**			**HT23**		
Start time	**Trip type 1**	**Trip type 2**	**Trip type 3**	**Trip type 1**	**Trip type 2**	**Trip type 3**	**Trip type 1**	**Trip type 2**	**Trip type 3**
05h00				100 km motorway			100 km motorway	100 km motorway	100 km motorway
06h00					100 km motorway	40 km rural			
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	

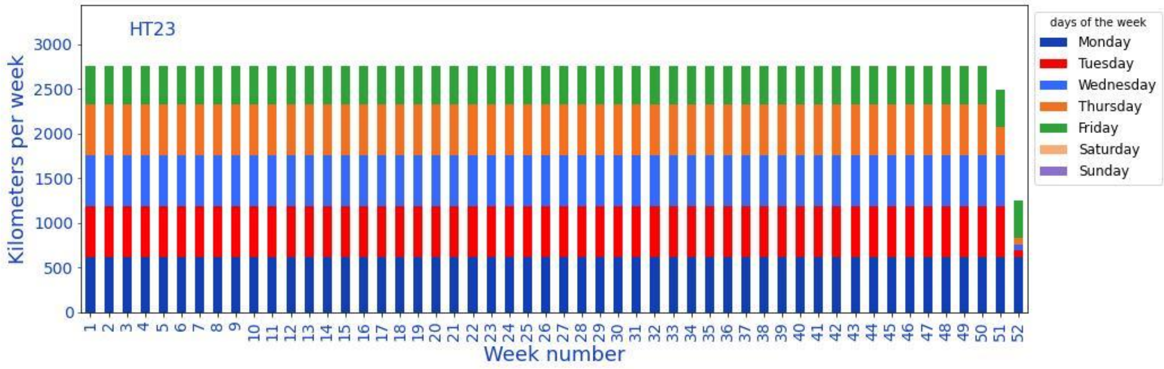
17h00									40 km rural
18h00						40 km rural	40 km rural	10 km urban	
19h00								10 km urban	100 km motorway
20h00							40 km rural		

Weekly kilometre profile charts for each archetype: HT11, HT12, HT22, HT23









B6 Buses

Table 30: 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, Periurban 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[34]. A week of service was taken, and modified to allow for charging.

HB12 – Low-floor bus, Periurban 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 31: trip definitions for low-floor buses, regional public transport service.

Start time	Trip type
08h00	5 km urban

[34] 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.

09h00	20 km rural
10h00	100 km motorway
13h00	40 km rural
14h00	10 km urban

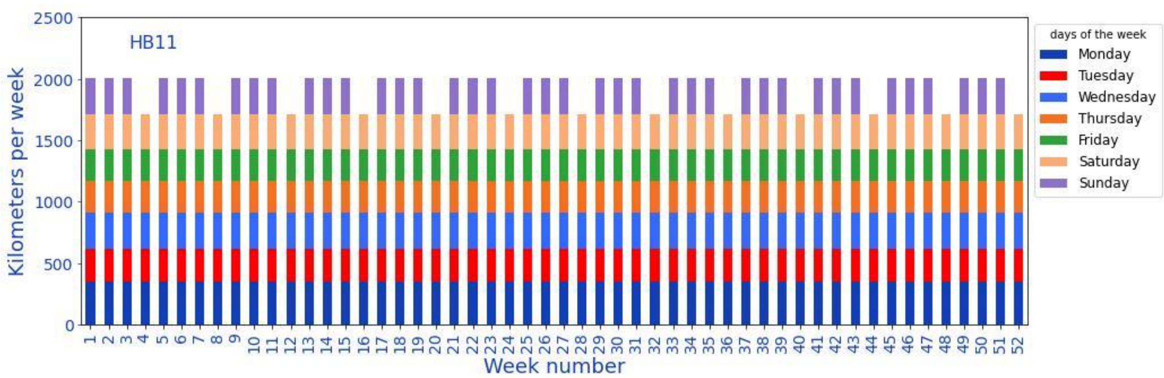
HB23 – High-floor coach, Long Distance Highway travel

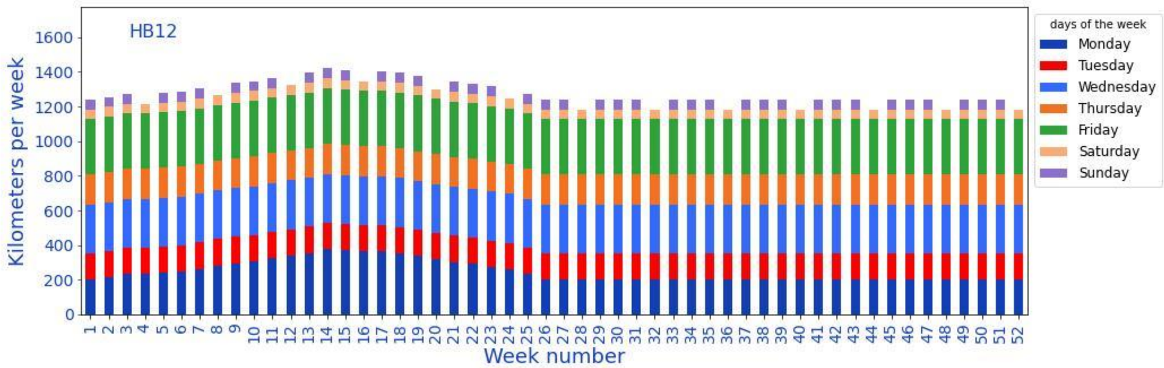
High-floor bus uses the same line/trip every day throughout the year for three times per week (on Tuesdays, Thursdays and Saturdays).

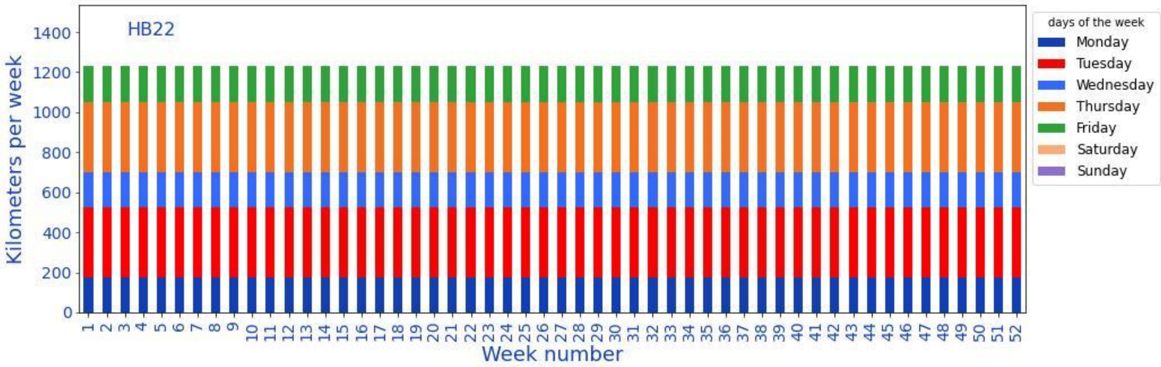
Table 32: trip definitions for high-floor coaches, long distance highway travel.

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

Weekly kilometre profile charts for each archetype: HB11, HB12, HB22, HB23

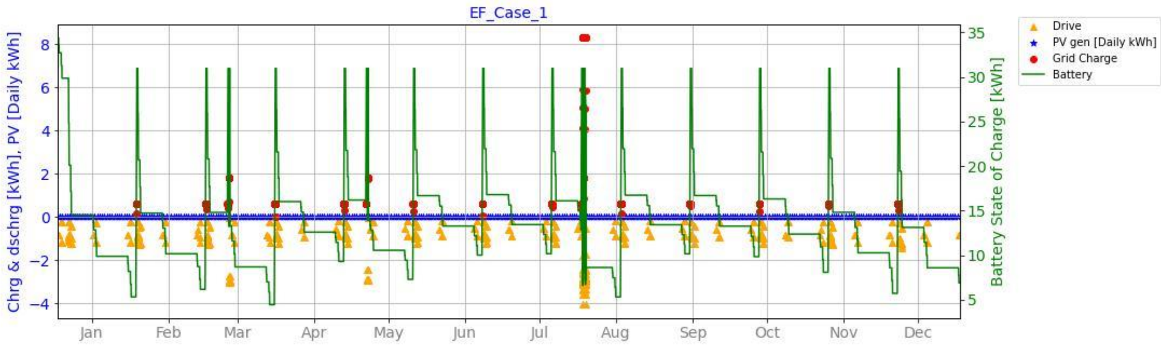


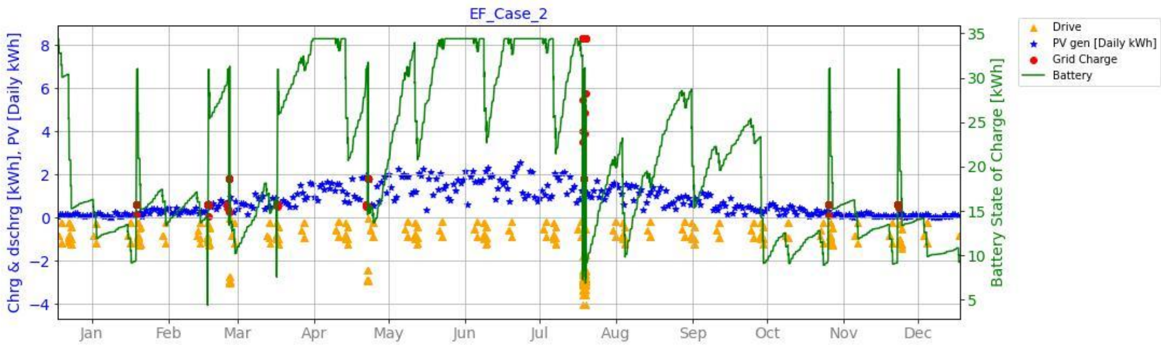


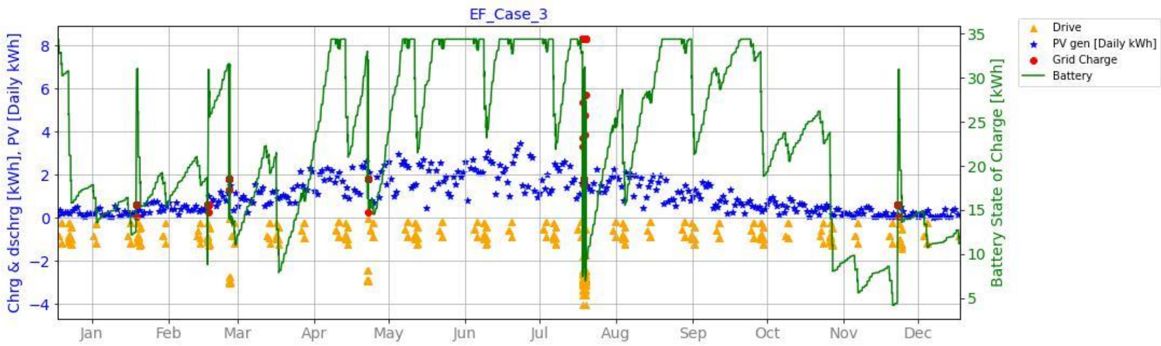

HB22
Kilometers per week
Week number
days of the week
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Sunday

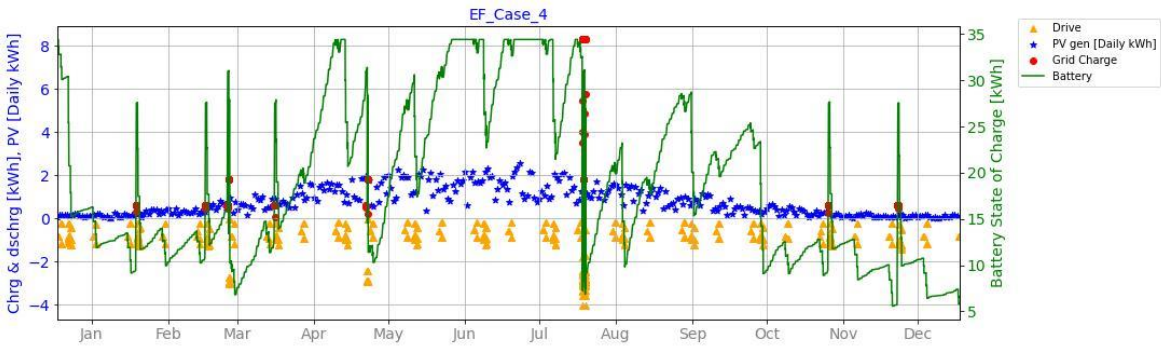
Appendix C Energy flow graphs

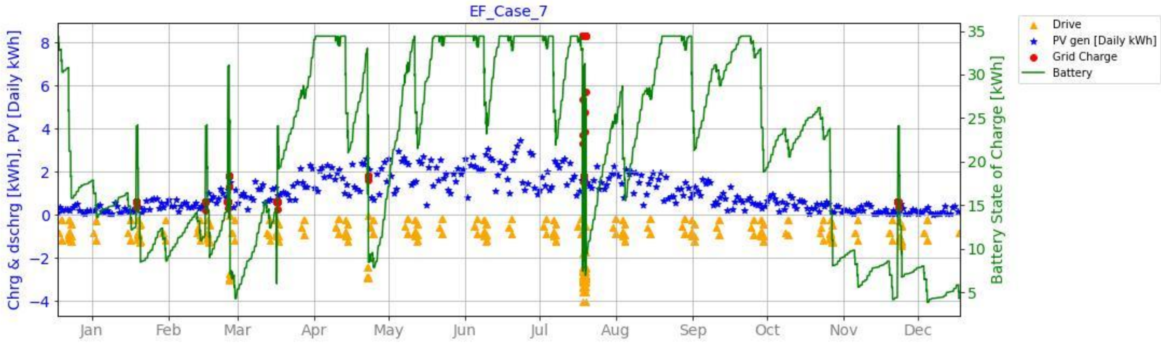
This appendix shows the energy flow graphs for the different archetypes for the Amsterdam situation without PV, with PV on sun facing surfaces and with PV on all sides.

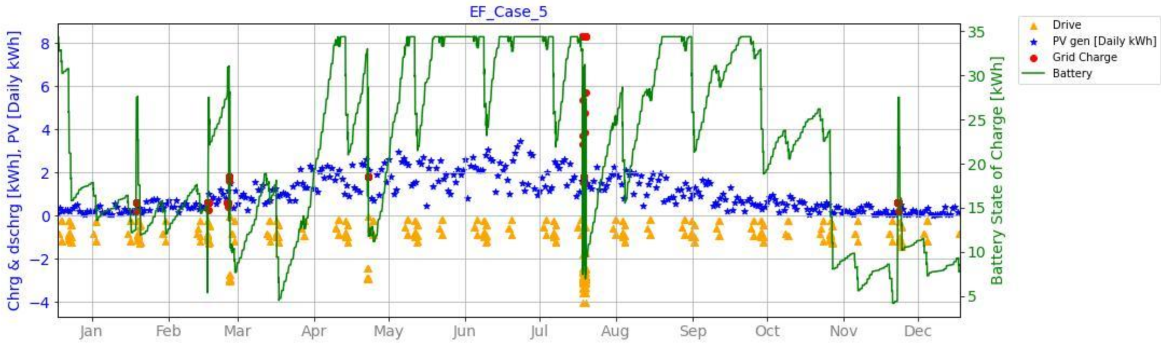


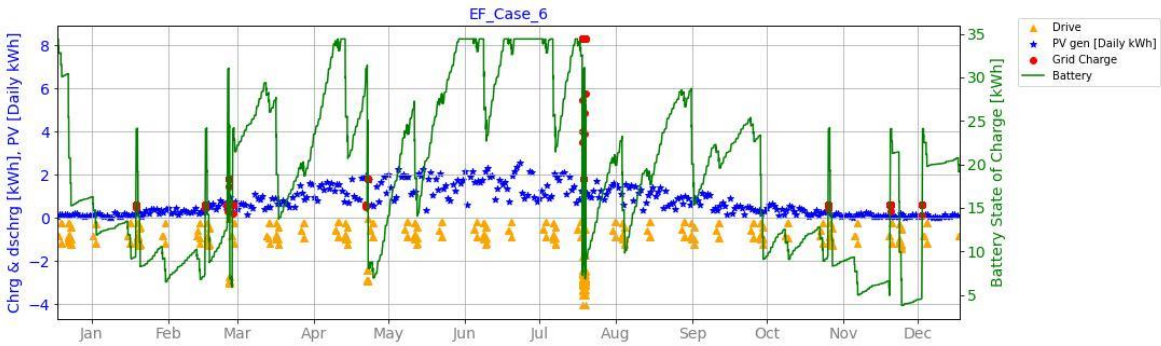







EF_Case_7
Chrg & dschrg [kWh], PV [Daily kWh]
Battery State of Charge [kWh]
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Drive
PV gen [Daily kWh]
Grid Charge
Battery


EF_Case_5
Chrg & dschrg [kWh], PV [Daily kWh]
Battery State of Charge [kWh]
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Drive
PV gen [Daily kWh]
Grid Charge
Battery


EF_Case_6
Chrg & dschrg [kWh], PV [Daily kWh]
Battery State of Charge [kWh]
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Drive
PV gen [Daily kWh]
Grid Charge
Battery

Appendix D Total cost of ownership

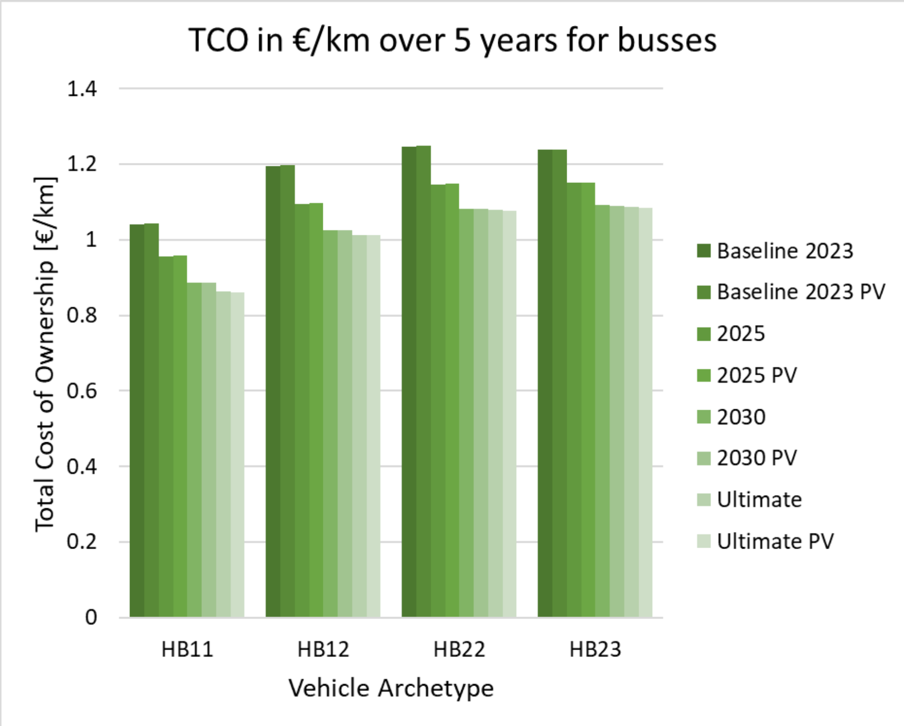


Figure 37 Total cost of ownership in euros per kilometre for different bus archetypes and different scenarios based on their efficiency improvements for an ownership of 5 years.

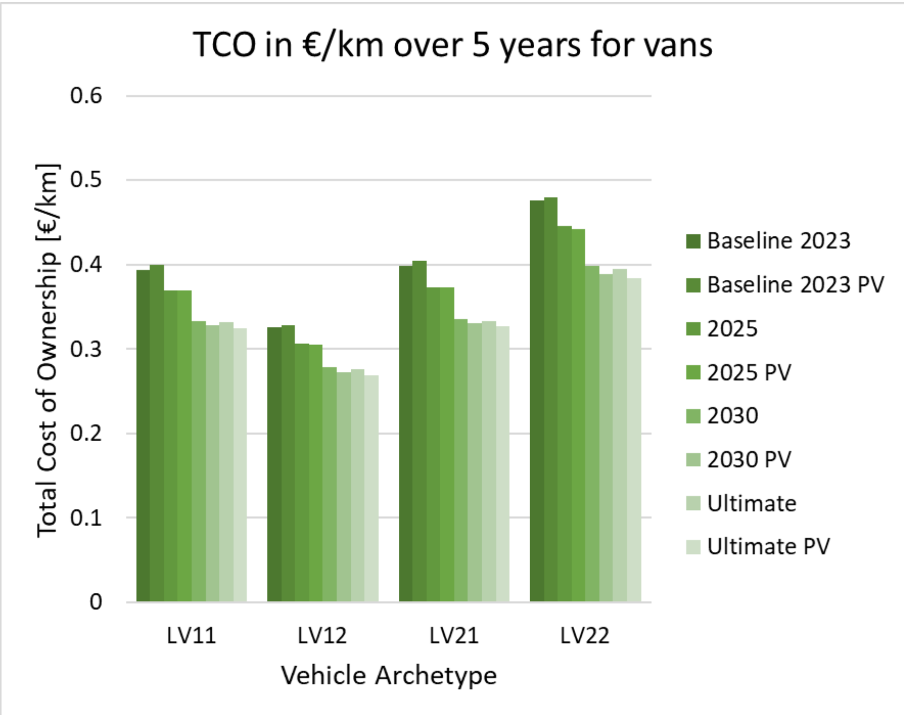


Figure 38 Total cost of ownership in euros per kilometre for different van archetypes and different scenarios based on their efficiency improvements for an ownership of 5 years.

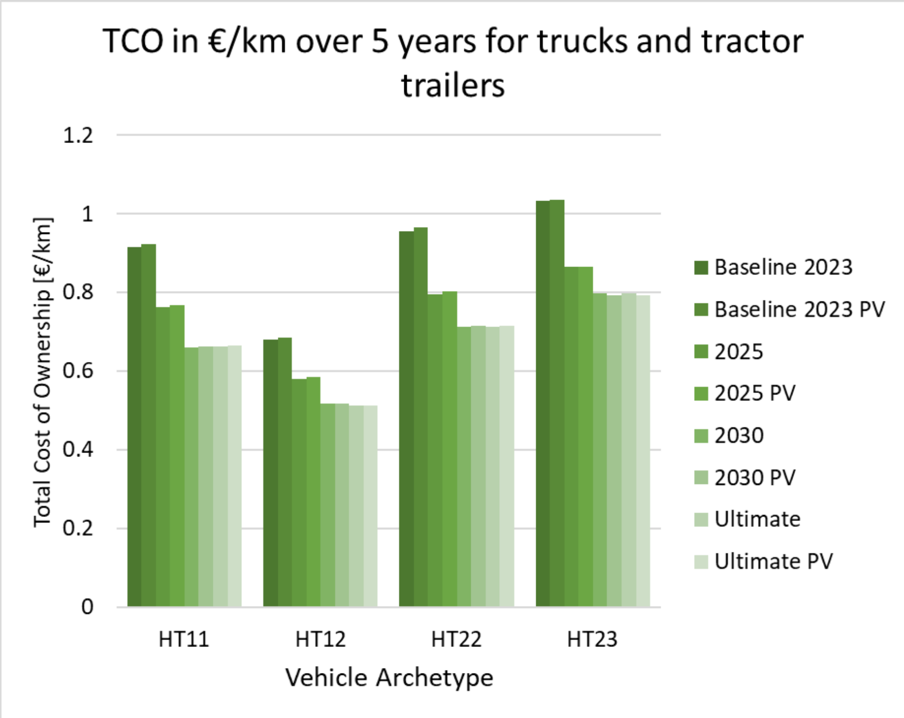


Figure 39 Total cost of ownership in euros per kilometre for different truck and tractor archetypes and different scenarios based on their efficiency improvements for an ownership of 5 years

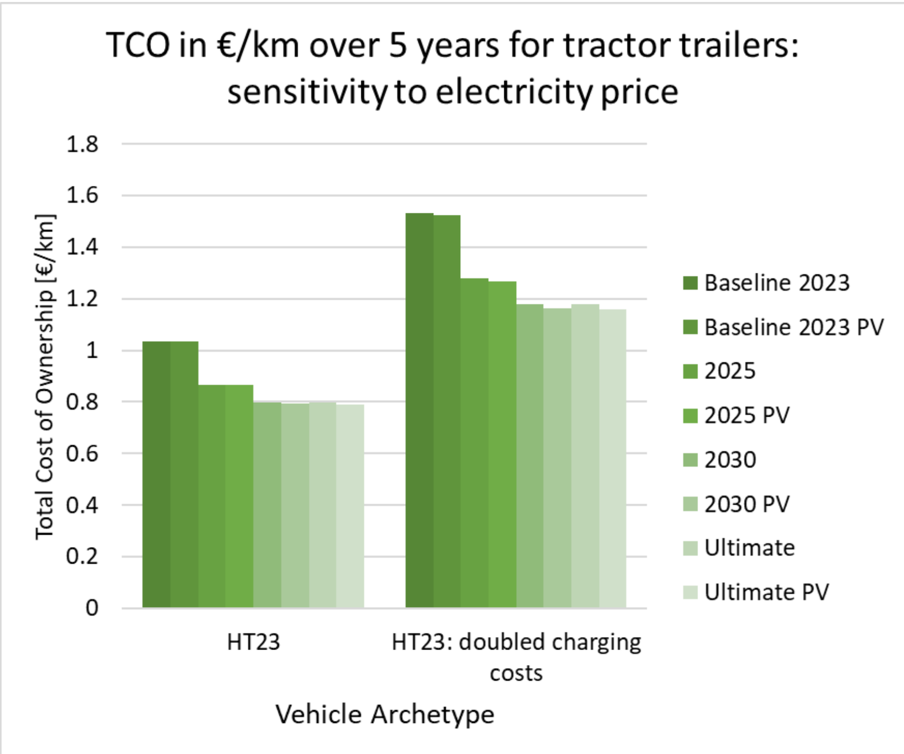


Figure 40 Total cost of ownership in euros per kilometre for long-haul tractor trailer for default and doubled charging costs, for an ownership of 5 years

Appendix E Zero-charging frequencies

Table 33 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 34 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 35 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 36 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 Energy consumption of auxiliary systems

Auxiliary systems other than airconditioning and heating

The auxiliary energy consumption of vehicles, excluding airconditioning 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) airconditioning 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[35]. 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:
   $$Cooling\ power\ [kW] = 0.0257 * (T_{ambient} - T_{inside}) + 0.1128$$
   $$Heating\ power\ [kW] = 0.0189 * (T_{inside} - T_{ambient}) + 0.0806$$
   For temperature difference above 14°C:
   $$Cooling\ power\ [kW] = 3.33e^{-4} * (T_{ambient} - T_{inside})^{2.77}$$
   $$Heating\ power\ [kW] = 2.44e^{-4} * (T_{inside} - T_{ambient})^{2.77}$$

[35] Evtimov, I., Ivanov, R., Sapundjiev, M., Energy consumption of auxiliary systems of electric cars, MATEC web of conferences 133, 06002 (2017).

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[36], is 13. UNECE data leads to the same number[37].

For coaches the same was assumed, based on an average of 30% that is reported by EEA; the information is outdated though[38].

[36] Eurostat PA_BUSCOA and TR_BUSCOA; https://ec.europa.eu/eurostat
[37] 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/
[38] EEA, long distance bus occupancy rates: https://www.eea.europa.eu/data-and-maps/figures/long-distance-bus-occupancy-rates, for years 2004-2008.