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Solar Moves: Part 1, Modelling the impact of VIPV

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ABSTRACT

In the Solar Moves project, the impact of vehicle integrated photovoltaics (VIPV) in reducing the stress on the electricity grid is studied. By determining typical driving profiles for a variety of vehicle types, looking at the impact of VIPV at vehicle and fleet level, and finally determining the energy demand on the grid compared to Electric Vehicles (EV's) without VIPV. Here, we focus on the impact of VIPV at vehicle level. Efficiency improvements in the vehicles and PV for future scenarios are calculated. Key findings show that in Southern Europe, VIPV could contribute up to 50 % of the energy requirement for common passenger vehicles. For Central Europe this would be 35 %. Finally the effect VIPV and other efficiency improvements in electric vehicles could have on the European Fleet shows that a reduction in grid electricity demand of 27 TWh in the EU could be possible in 2030.

1. Introduction

Part of the energy transition is the transition from fossil fuel-based transport to electric transport. This electrification of the transport sector will result in an enormous increase in the electricity demand in all sections of the electricity grid as the charging will take place at home, on the street, in charging hubs, or along highways. This will require grid reinforcements and also a substantial increase in generated renewable energy to provide these charging stations with green energy. VIPV on the other hand will generate the electricity where it is needed and does not need electrical infrastructure to charge the car. The model described here is able to determine the impact of the integration of PV on a large number of different but representative vehicles with different driving profiles and the results can then be used to create a fleet for either a country or for a neighbourhood.

Through use of TNO's MEO (Multi-level Energy Optimisation model) and EFM (Energy Flow Model) [1–3], 23 archetypal vehicles and associated driving profiles have been created and assessed through simulations. Looking at 2 locations: Amsterdam and Madrid, with and without PV, and employing various charging strategies, we have quantified the contribution that integrated PV can make on the energy and charging requirements of the different archetypes. From the simulations we calculate the energy [Wh] required from grid charging. In this way we see the improvement from having no PV to having PV on the roof, or on the roof and sides.

The driving profiles have been constructed based on a variety of use patterns which have then been translated into the actual energy required by the vehicle per timestep.

We investigate further efficiency improvements in the vehicles themselves in combination with PV, thereby determining what may occur in the future as vehicles and PV deliver better performance.

Fig. 1 shows the workflow and steps employed in the process to determine the grid requirements for EV's with and without VIPV.

2. Vehicle archetypes

Defining vehicles and driving profiles to represent the Netherlands and European fleet.

Table 1 shows the vehicles and use patterns that have been defined and studied. For each vehicle type a 'typical' vehicle has been defined based on the average properties of the top 5 or top 10 most sold EV's in the EU per category for the years 2020, 2021 and 2022. The sales data is obtained from EAFO (European Alternative Fuels Observatory) [4]. Properties of these vehicles include: battery capacity, weight, dimensions, motor power, etc. The use patterns are characterised by: annual mileage, road types and trip. lengths, and have been defined based on several data sources including for the Dutch fleet from the Central Bureau of Statistics (CBS) [5] and the European averages [6].

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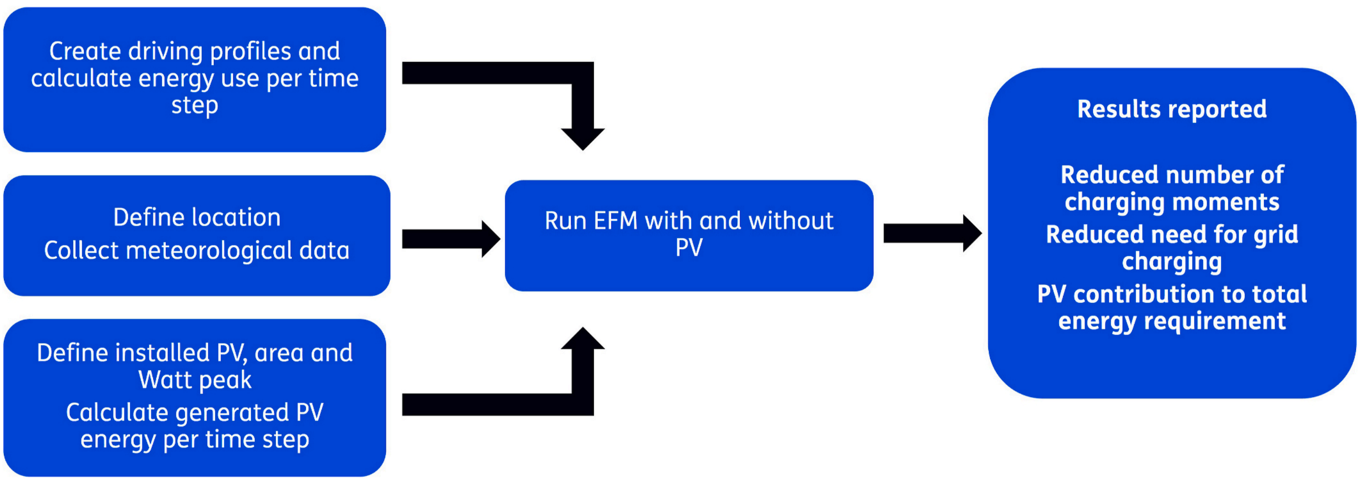

Fig. 1. Workflow for determining the impact of VIPV on the demand for grid energy.

Table 1
The vehicle and use pattern for each chosen archetype. Column 'Code' refers to the code as used in the other graphs and tables.

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

Fig. 2 shows an example of an annual driving profile, in this case LP22, the medium sized passenger car with a daily semi-urban commute, and an annual mileage of just over 10,000 km. The profile is given as weekly totals that are broken down into days of the week, shown by the different colours.

2.1. Calculations of energy demand of vehicles

2.1.1. MEO model – Multi-level Energy Optimisation

The MEO model developed by TNO [2,3] is a physics-based model that calculates the power required at the wheel from the vehicle characteristics and for the specific driving profile. The power at the wheel is calculated using the following equation. (1)

$$P\ wheel\ [kW] = P\ Inertia\ [kW] + P\ Rolling\ [kW] + P\ Gradient\ [kW] + P\ drag\ [kW] \tag{1}$$

Where.

P wheel [kW]: Power required at the wheel
P Inertia [kW]: Power required to overcome resistance to change in velocity.
P Rolling [kW]: Power required to overcome rolling resistance
P Gradient [kW]: Power required to overcome road gradient
P drag [kW]: Power required to overcome drag due to shape of vehicle

On top of that, we assume a constant auxiliary energy usage

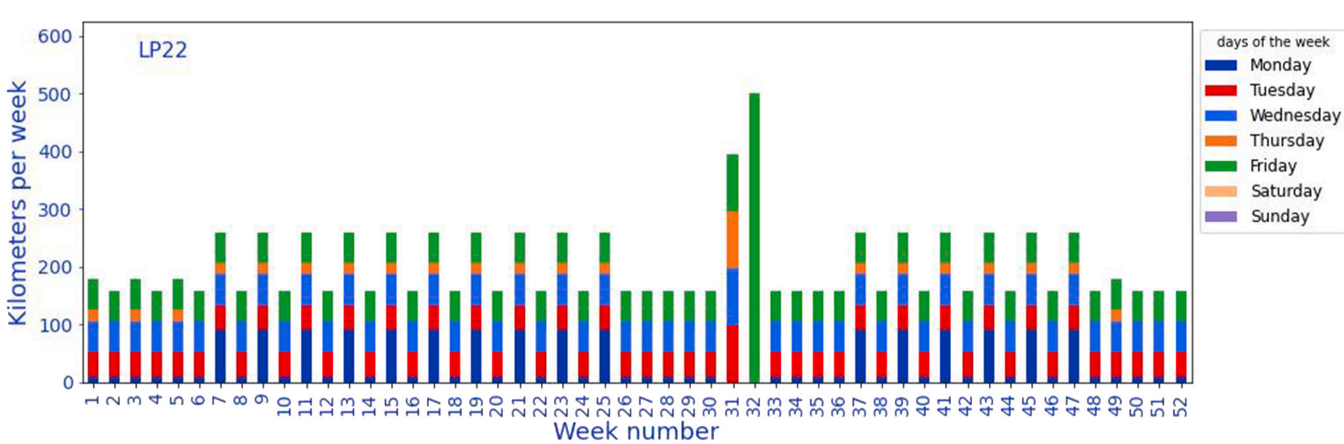

Fig. 2. Example driving profile showing weekly kilometres driven for each week of the year, broken into daily totals given by the different colours.

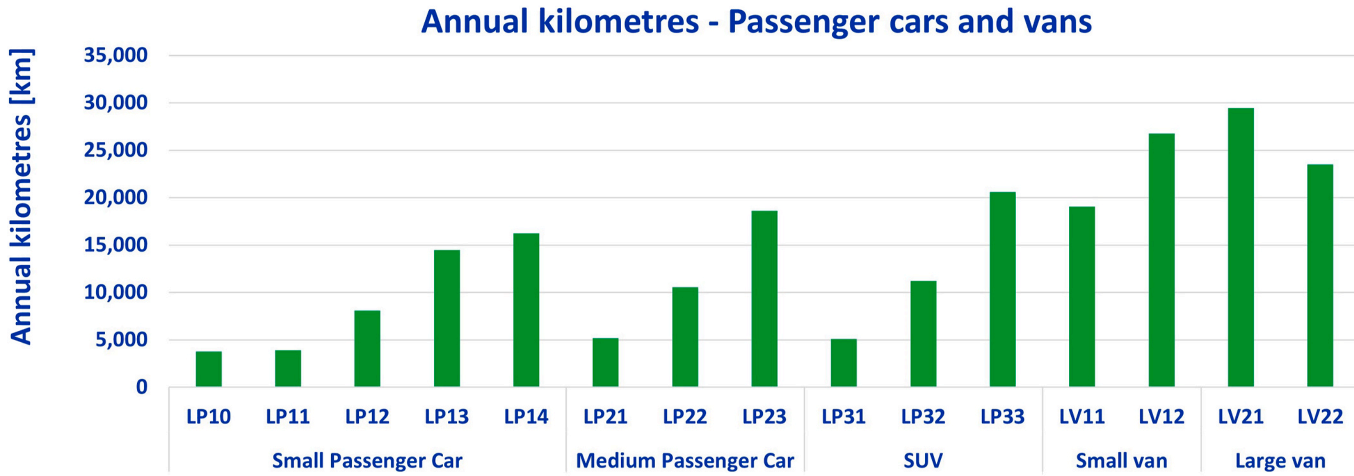

Fig. 3. Annual mileage for passenger cars and vans.

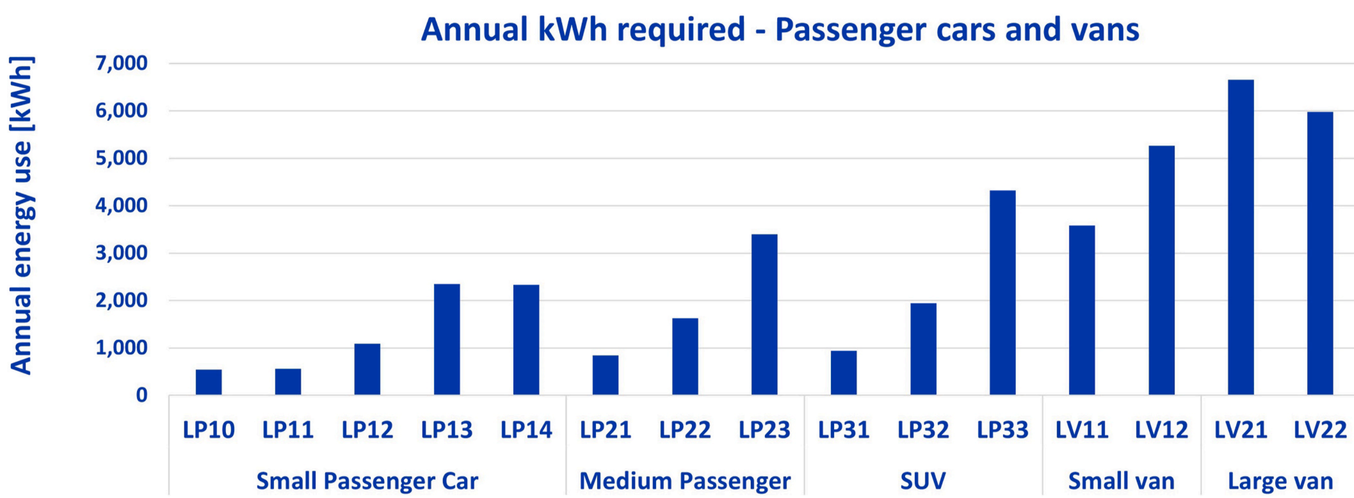

Fig. 4. Annual energy requirement per archetype (passenger cars and vans). This is the total energy required from the battery to travel the given distance, it includes the energy required for the heating and air-conditioning loads. It does not include the charging losses.

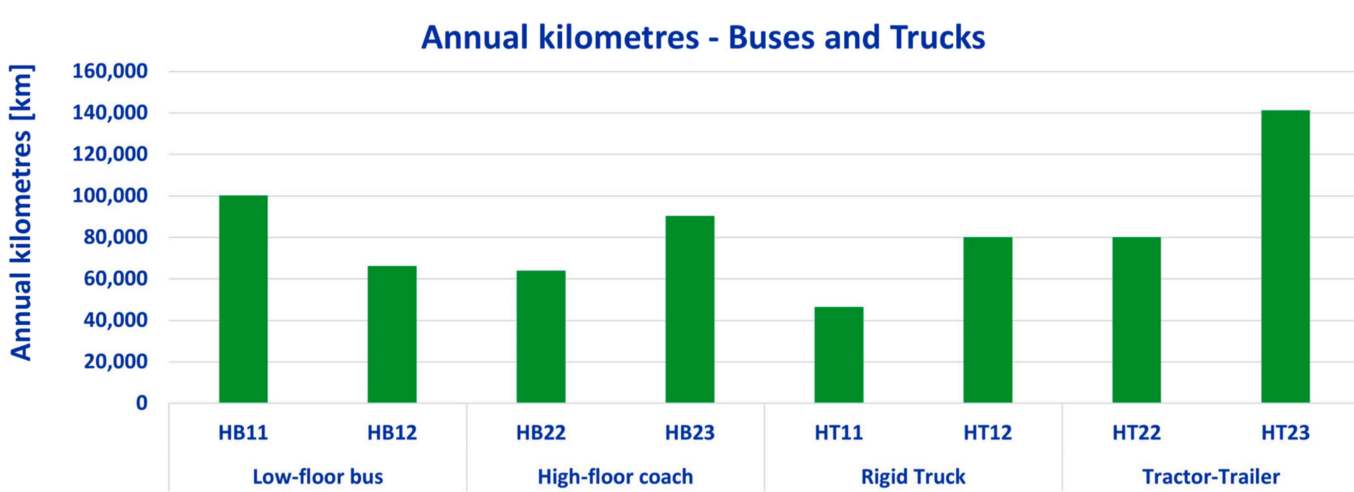

Fig. 5. Annual mileage for buses and trucks.

(magnitude depending on the type of vehicle). The includes lamps/wipers/radio/ECU etc … The power required for air-conditioning and heating is calculated separately using the outside temperature values per time step and location, where driving in Madrid would likely call for more air-conditioning and driving in Amsterdam more heating.

Figs. 3–6 show the mileage and energy needs for each of the

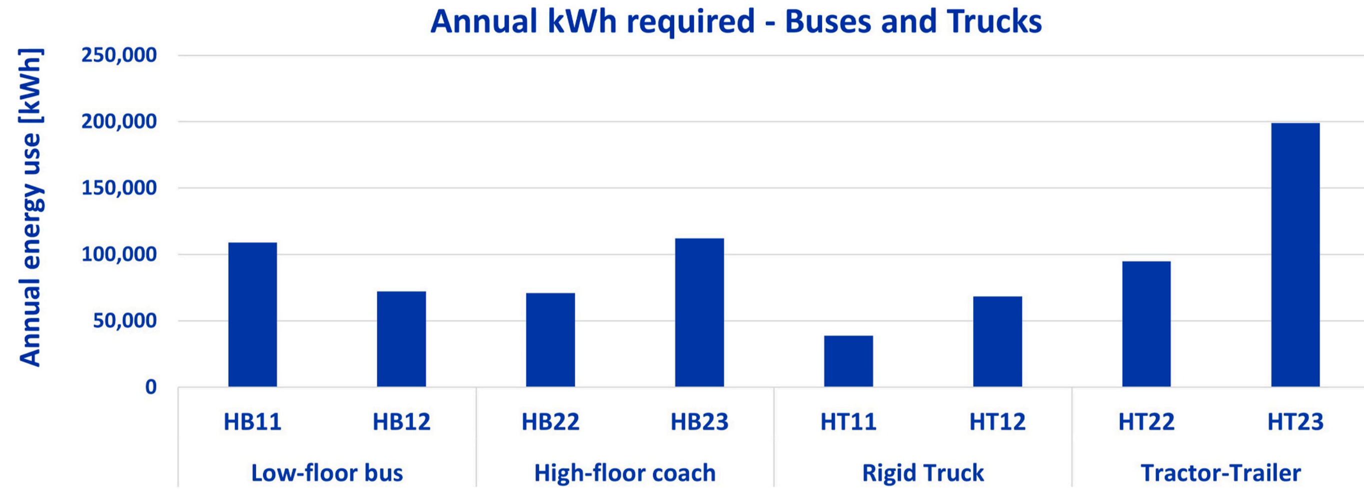

Fig. 6. Annual energy requirement per archetype (buses and trucks). This is the total energy required from the battery to travel the given distance, it includes the energy required for the heating and air-conditioning loads. It does not included charging losses.

Table 2
Cost-effective efficiency improvement 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

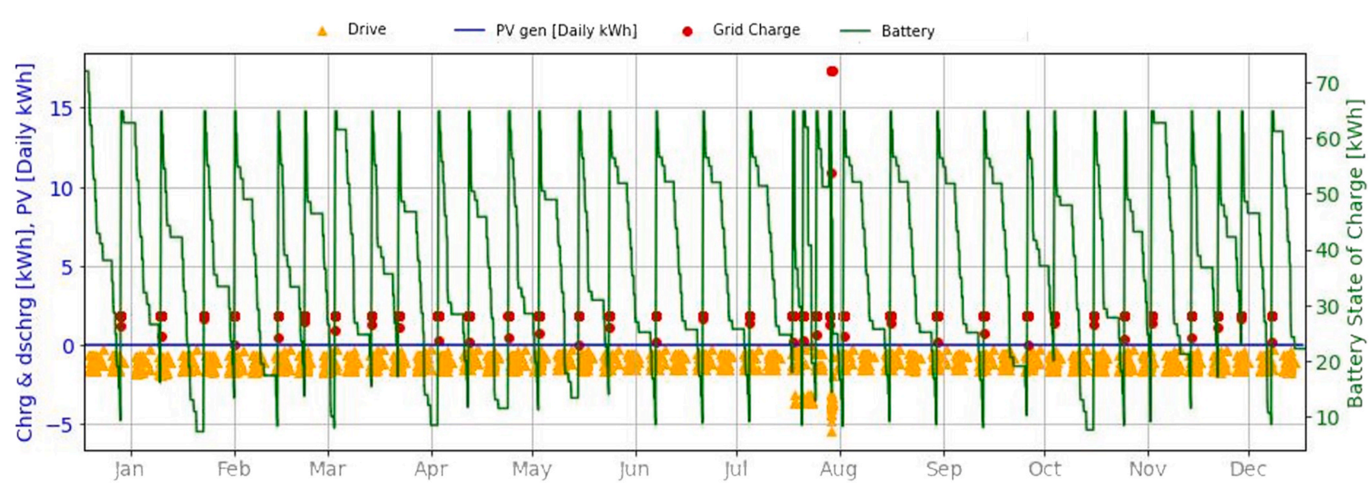

Fig. 7. The energy flow time series of the example, showing the 37 charging moments over the year, as indicated by the red dots.

archetypes, the annual kilometres are part of the archetype definition process and the energy required is calculated using the MEO model for the Amsterdam location.

2.1.2. Vehicle efficiency improvements

To understand future implications of VIPV and EV impact on charging infrastructure various vehicle cost effective efficiency improvements have been considered, these include reducing rolling resistance through better tyres, weight reduction and improved aerodynamics. The inclusion of PV is also considered an efficiency improvement as it reduces the need for grid charging. Table 2 gives an example of the cost effective efficiency improvements in 2025 and 2030 for small passenger cars, as well as the ultimate situation where all efficiency improvements are taken into account, whether they are cost effective or not.

In the calculations, a PV module efficiency of 21 % and a flat

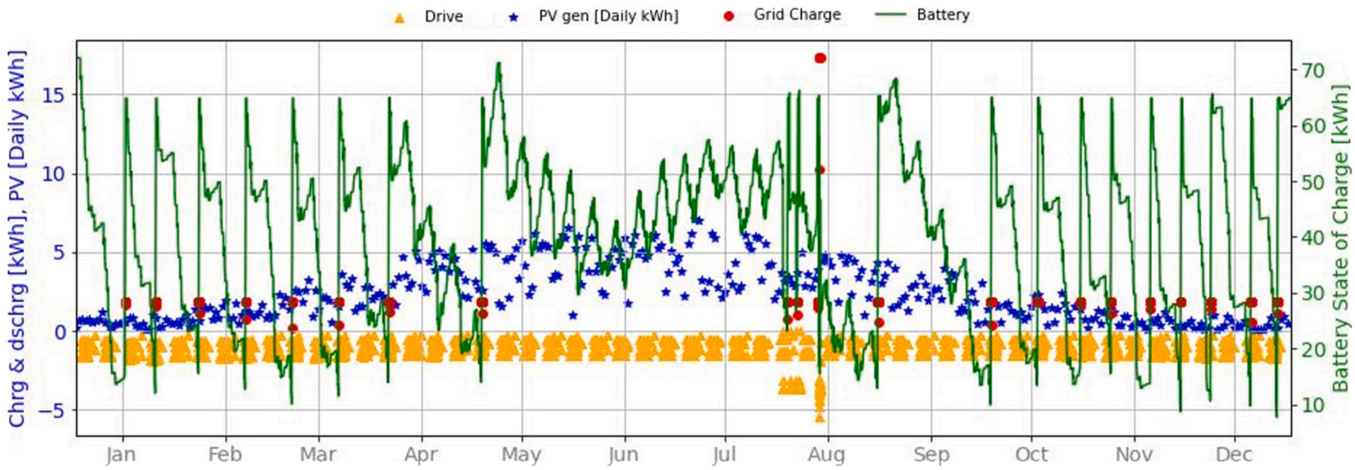

Fig. 8. The energy flow time series for the variant with PV on the top and sides, showing the 23 charging moments over the year, as indicated by the red dots.

Table 3
Vehicles specifications provided 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.

		Available PV area [m^2]		Charge rates [kW]		
Vehicle type	Useable 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 and 11**	**11**	**49.7**
Medium passenger car	59.0	2.64	0.95	**3.6 and 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**

Table 4
Fixed parameter setting used in every simulation.

Parameter	setting	comments
Battery minimum SOC	**10 %**	
Maximum SOC, Base, Street or Work charging	**90 %**	**Unless strategy B is used (see paragraph 3.2.1) then limited by space allowance setting for PV.**
Maximum SOC highway fast charge	**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**
Charge factor losses		
Base, Street or Work – loss	**15 %**	
Highway fast charge (DC) – loss	**10 %**	
PV charging loss	**4.5 %**	
PV elements		
PV efficiency	**21 %**	**Used to calculated PV installed and PV yield given m2 available for PV**
PV tilt angle	**0° or 90°**	**The PV element is either horizontal for the sun facing surfaces, or vertical for PV on the sides**

horizontal surface was assumed. The module efficiency also depends on the packing density or active area and will in the case of VIPV depend on the curvature of the VIPV laminate as well, as a strong curvature in general leads to lower packing density. In the modelling the packing density is not explicitly taken into account. The mentioned efficiency improvement can be the result of PV efficiency improvement on cell and module level including an increased packing density.

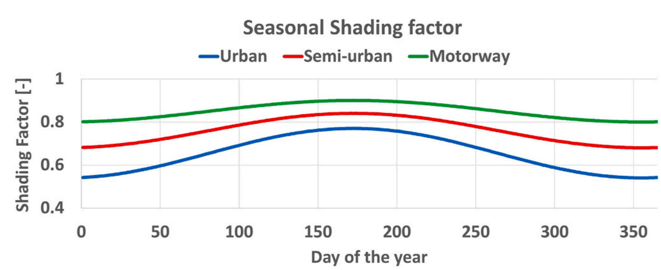

Fig. 9. Seasonal shading factor for different road types. The shading factor is the fraction of the solar light received by the VIPV during a trip on a certain road type in comparison to the amount of solar light received on a trip without any shading losses.

3. VIPV modelling

3.1. Description of the energy flow model for VIPV

The energy flow model calculates the state of charge (SOC), of the battery, taking into account the charging, the energy needed for driving and the auxiliary system. This includes the use of air-conditioning or cooling also for refrigerated trucks as determined by taking into account the ambient temperature.

TNO's Energy Flow Model (EFM) [1] is a detailed energy balance model of vehicle energy use and on-board PV yield. This is calculated as a time series over a whole year to be able to account for seasonal effects, especially on PV yield. It takes the meteorological conditions and the installed PV to calculate the PV energy generated per time step to map the energy going in and out of the battery. In doing so it is able to

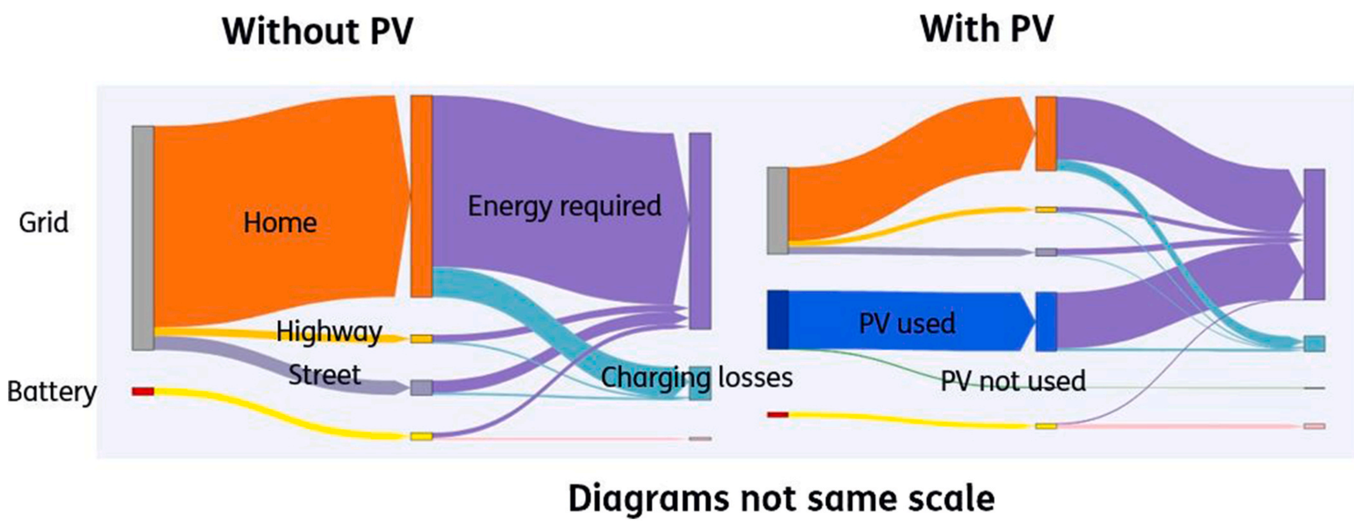

Fig. 10. Energy flow diagram showing the results for with and without PV for LP32, The SUV with 11230 km/year (seen in Fig. 7). These two images do not have the same scale. However we see proportionally that when PV is introduced it contributes a significant amount to the total energy requirement, over 40 %.

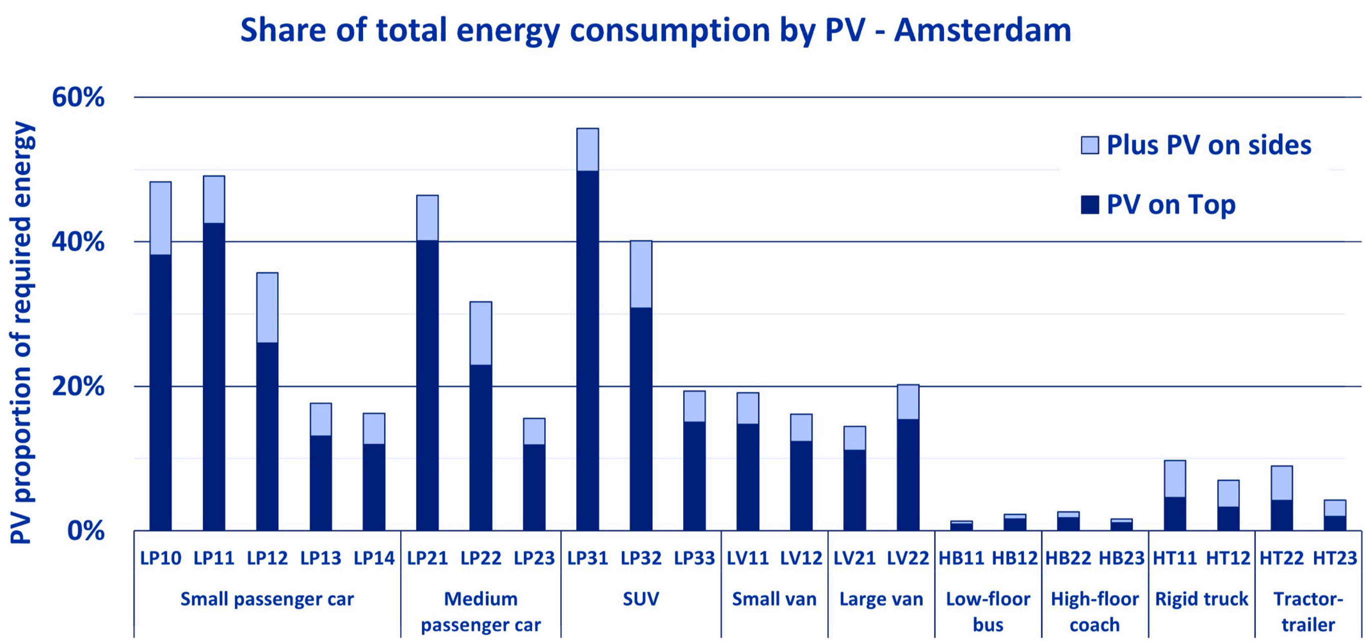

Fig. 11. Share of total energy consumption provided by PV for each archetype for Amsterdam.

ascertain how many charging moments are required over the year as well as how much the PV energy is able to contribute to the total energy needs.

3.1.1. Example output – time series

Figs. 7 and 8 show an example of the output of the energy flow model for an SUV passenger car with a 72 kWh battery and an annual mileage of 11230 km/year. Fig. 7 shows the situation without PV, Fig. 8 for PV on all surfaces.

In blue, the daily energy generated by the PV is depicted, in green the battery SOC (right axis) and in orange the energy needed for driving. Here negative values indicate energy consumption. The red dots indicate the charging moments, when the vehicle was connected to the grid. When PV is introduced to this archetype the battery state of charge is above 50 % of its maximum for much of the year 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.

The next step is to identify the effect of other energy improvement options for 2025 and 2030 to see if PV on the vehicle is a viable option or that other improvement options are more suitable from a cost perspective.

3.2. Assumptions and input settings for the energy flow model

The main assumptions used in these simulations are that the PV is horizontal or vertical when on the sides of the vehicle and no curved PV or other angles are considered. We also assume a baseline efficiency for the PV of 21 %.

Shading effects are included (see 3.2.2), as is the direction of travel or bearing angle when PV is installed on the sides of a vehicle.

Meteorological data per location consists of, GHI, DHI, ambient

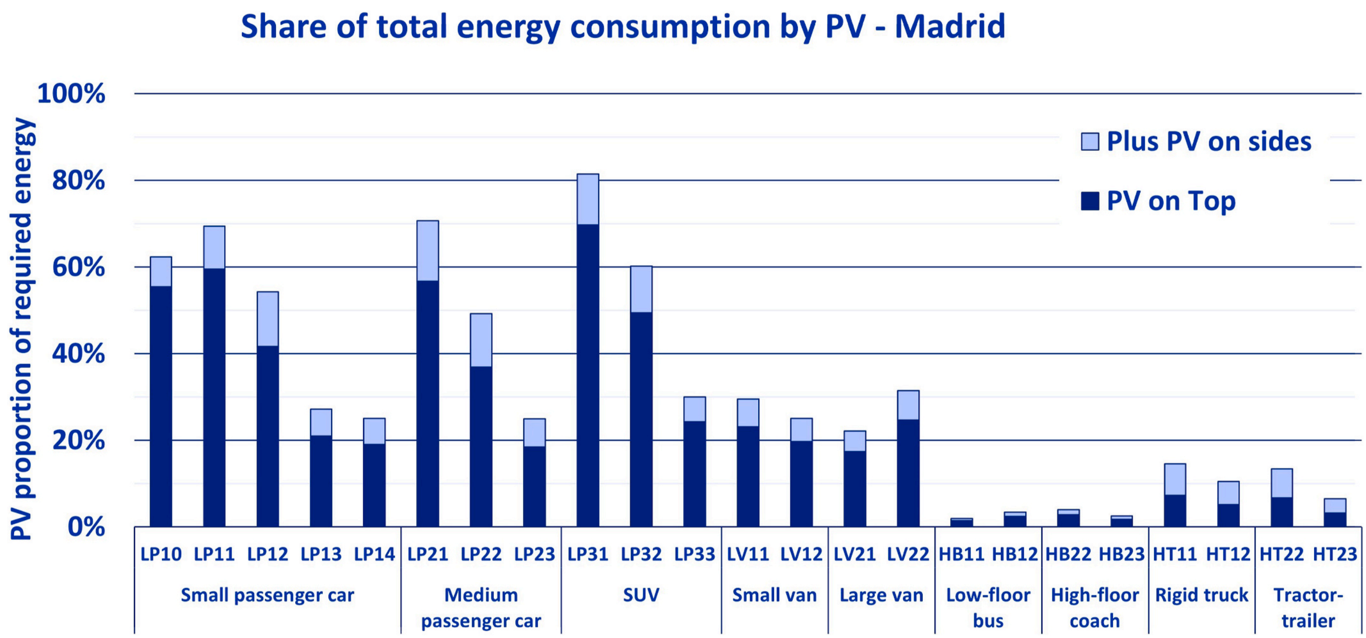

Fig. 12. Share of total energy consumption provided by PV for each archetype for Madrid.

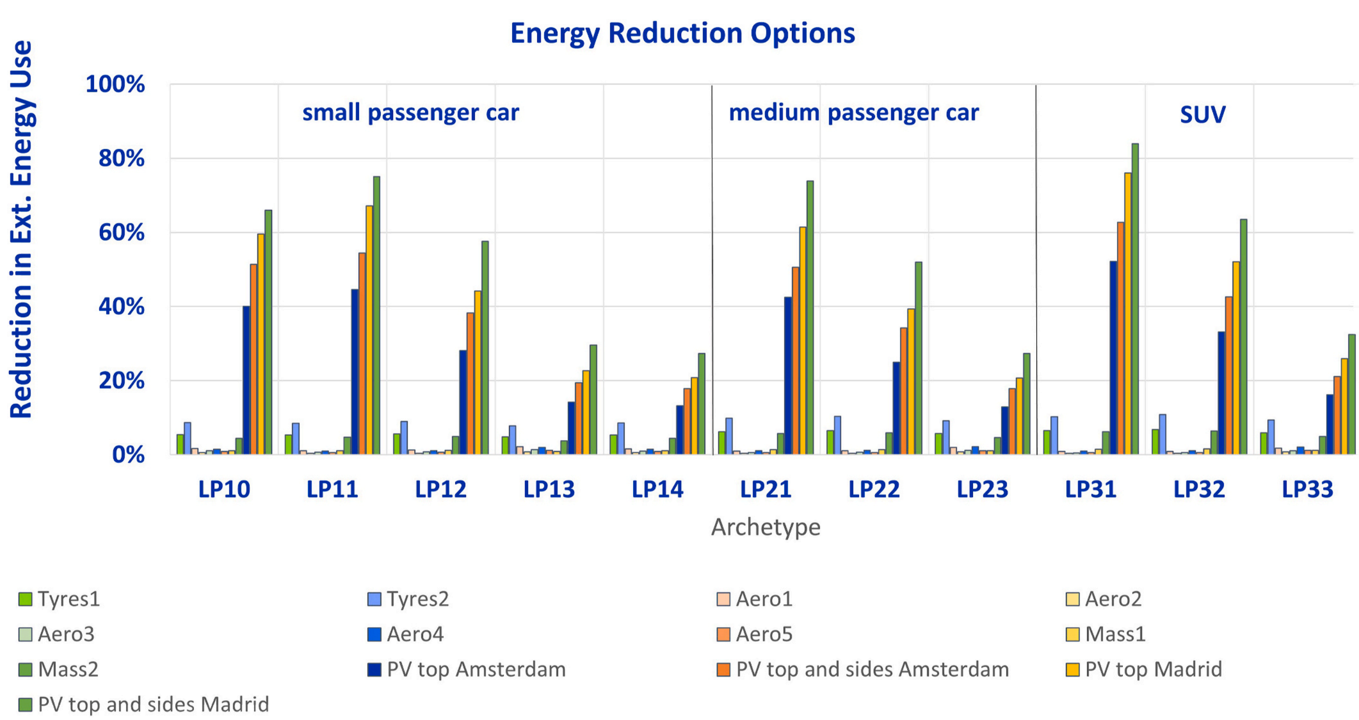

Fig. 13. Reduction in external energy consumption for each efficiency improvement for passenger cars. This is relative to the energy consumption of the Amsterdam baseline (2023) vehicle. Here it can be seen that the PV has a considerable impact compared to the other improvements.

temperature and windspeed with a 10 min time step, as derived from the Meteonorm data source [7].

Each archetype consists of.

- vehicle specifications
- driving profile
- shading factor,

Where the vehicle specifications consist of: useable battery capacity, available PV area, charge rates and losses, see Table 3.

All the archetype time series driving profiles include the date and time, kWh required per time step, km travelled per time step and the location per time step. The location is not the main location used for meteorological date but the actual location of the vehicle to determine what kind of charging is available. As can be seen in Table 3, the possible choices are: Base or home, Street or work, and Highway for fast charging options. To account for the type of charging possibility people have at home, there are two charging rates chosen for base or home rate. The value of 3.6 kW is for people who have off-street parking or can charge from their own home electricity supply, and 11 kW is for people who

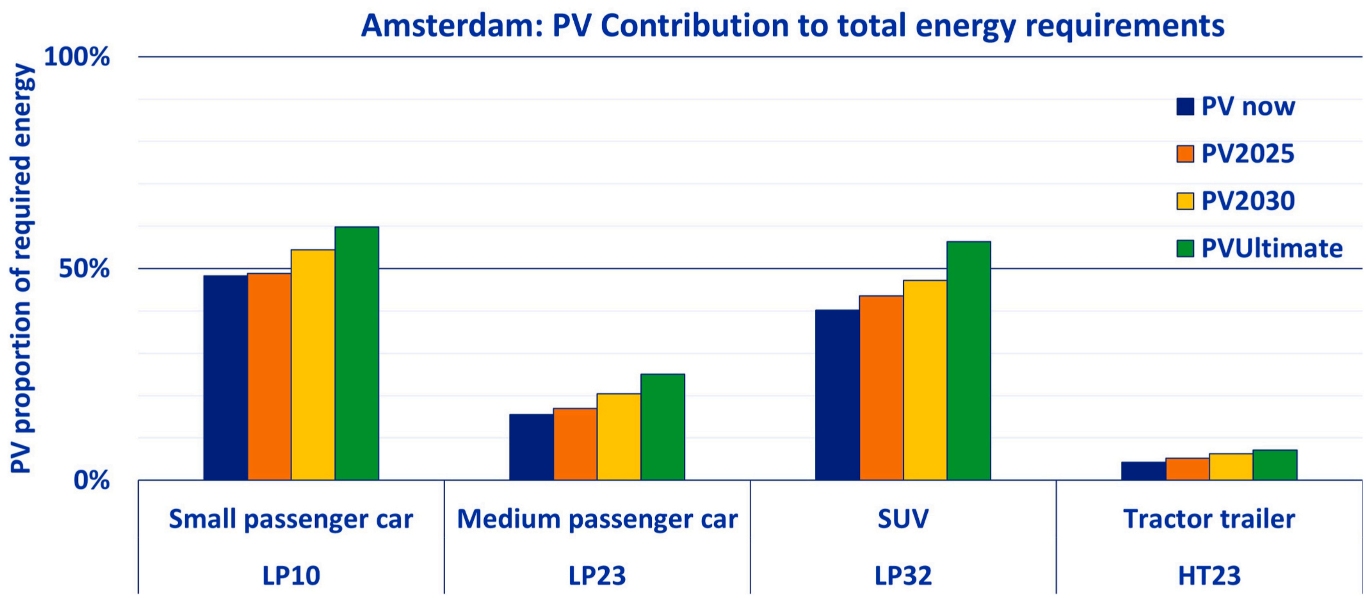

Fig. 14. The contribution from PV now and in the future for a selection of archetypes in Amsterdam.

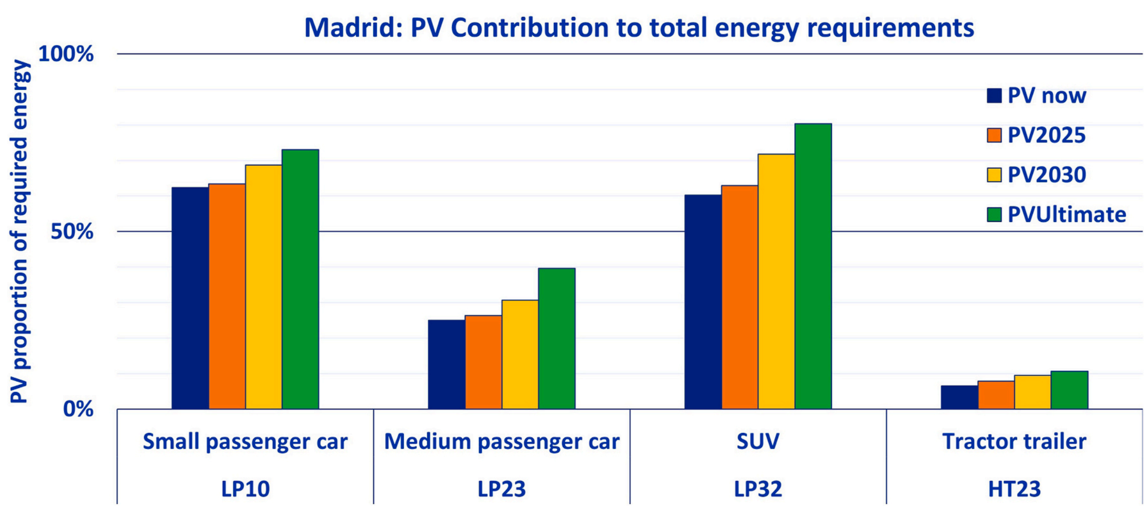

Fig. 15. PV contribution now and in the future for a selection of archetypes in Madrid.

only have access to public street charging while at home. Table 3 also shows the vehicle specifications and the PV area that have been used in the simulations. An extra field, bearing angle, is included in the time series input. This is applied to each time step to account for PV integrated in the sides of a vehicle. A separate study confirmed that a bearing angle of 45° while driving is a good approximation to an average of best orientation, 0° (North – South travel), and least favourable of 90° (East – West travel). This is applied to all time steps while driving. And a random value between 0o-360o is applied to all times when the vehicle is parked.

Other fixed setting used in all the simulations are given in Table 4

3.2.1. Charging strategies

The EFM has several charging strategies to model different owner behaviours. For each simulation separate calculations were made for 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 h

3.2.2. Shading

There is not much information on the shading on cars induced by buildings and trees along roads. The thesis of Cobbenhagen [8] 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. [9] 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 here. The numbers are based on the latitude of Amsterdam. For this work the intermediate numbers have been used to take into account the fact that in the Netherlands you hardly have completely open areas and the Urban

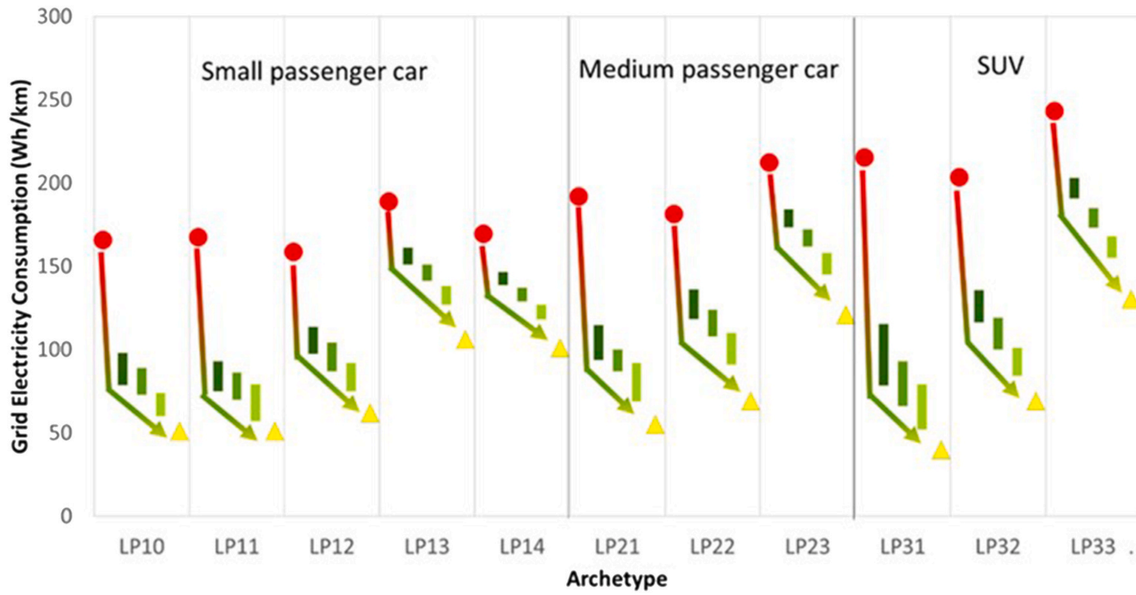

Fig. 16. Amsterdam grid electricity consumption for and electric passenger car, showing evolution and reduction of energy demand as efficiency improvements are applied. The arrows are a guide for the eye. Table 5 provides a key for this graph.

Table 5
legend for Fig. 16.

●	*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 %***

Table 6
Share of battery electric vehicles in the EU27 fleet in 2023, 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 %

routes are often a mix between real city centre and more low-rise residential parts. The height of the vehicle is not part of the shading loss calculation. The seasonal shading factors are shown in Fig. 9 and result in an average annual shading loss of.

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

3.2.3. Summary of simulations

When combining all the variations in PV, (none, sun facing surfaces, sun facing surfaces and sides), the different charging strategies and their variations, the different charge rates for small passenger cars at home or on the street, we required in total 372 simulations per location per year, 2023 (now), 2025, 2030 and what we called Ultimate.

The first sets of simulations (2023) served as a benchmark to then compare the impact of possible efficiency improvements.

4. Results

The first results we consider are the baseline results for the individual archetypes, looking at the PV contribution to the energy requirements. We then consider the effects of efficiency improvements and finally consider the impact, in terms of grid energy reduction, on the European fleet.

4.1. PV contribution to total energy requirements

Fig. 10 shows the energy flows from source, grid, battery or PV to the final energy required for the case of the SUV with an annual mileage of 11320 km. In this case the car without PV is predominantly charged at home, with some highway and street charging. When PV is introduced it contributes a significant amount to the energy needs. This is because the car has a large PV area, and a large, 72 kWh, battery which can absorb and store the PV energy that is generated, ensuring that 100 % of the PV energy is utilised. This is of course not always the case and depends very much on the mileage, battery size, amount of PV installed etc.

In Figs. 11 and 12, the PV contribution is shown for all archetypes, for Amsterdam and for Madrid. For Amsterdam the contribution from the PV ranges from 1 to 2 % for the buses, which have high mileage and energy use, up to around 55 % for LV31, the SUV with a low annual mileage of approximately 5000 km.

In Madrid, Fig. 12, the contribution of the PV is higher for all archetypes, due to the fact that there is a much higher solar resource available. Here we see a contribution of more than 80 % for LP31, the SUV with 5000 km/year mileage. LP32 the SUV with 11320 km/year sees a 60 % contribution from the PV. And there is more than 20 % for all the passenger cars and vans.

4.2. Effect of vehicle and PV efficiency improvements

A series of efficiency improvements were implemented in the simulations to understand what the impact could be on the European fleet and energy demand into the future. Table 2 shows some cost effective improvements that were identified for small passenger cars and Fig. 13 illustrates what the impact of these efficiency improvement will be for reducing the external energy required in the case of the passenger cars. This was also done for the other vehicles and a new set of simulations was performed to represent the situation in 2025, 2030 and an

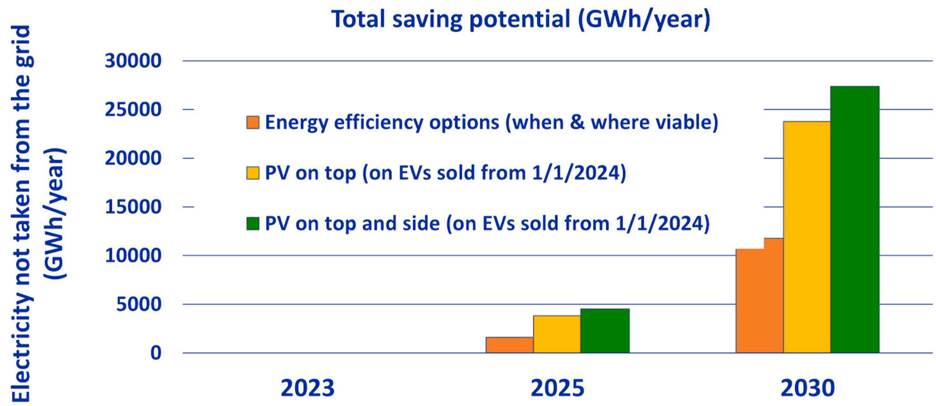

Fig. 17. Potentially avoided grid electricity consumption resulting from vehicle efficiency improvements and VIPV for the projected EU fleet, EU27. Baseline = 2023 vehicle efficiency and no VIPV. Additional fleet only = only newly sold vehicles from 1/1/2024 onwards.

'Ultimate' scenario where all improvements are applied.

As can be seen in Fig. 13, the PV contribution is much higher than the contribution of the other efficiency improvements. Of course the contribution decreases with increasing mileage, compare.e.g LP11 with LP14.

Figs. 14 and 15 show the PV contribution to the total energy needs for four of the archetypes for Amsterdam and Madrid respectively. The increase in PV contribution for the future scenarios is clear, as the vehicles and PV become more efficient the total energy required is reduced, and the total yield from the PV is increased leading to a higher contribution from the PV. The 60 % contribution seen in the baseline case for LP32 (SUV with 11320 km/year) in Madrid has increased to 80 %, and in Amsterdam it has gone from 40 % to around 56 %. The tractor trailer, HT23 with approximately 140000 km/year also experiences an increase in PV contribution. For Amsterdam it increases from 4 % to 7 %, and in Madrid from 6 % to 11 %. The small car sees an improvement from 50 % to 60 % in Amsterdam, and from 62 % to 73 % for Madrid, and the Medium car with higher annual mileage sees the PV contribution go from 16 % to 25 % for Amsterdam, and from 25 % to 40 % for Madrid.

Fig. 16 shows the grid energy consumption per kilometre results with respect to the efficiency improvements over time for the passenger cars, the red dots show the baseline situation in 2023, with each subsequent improvement being applied and resulting in a reduction of required grid energy per km. The introduction of PV has the largest impact, especially for the lower mileage archetypes.

4.3. EU fleet construction and impact

By combining Dutch historic and predictive EV fleet development curves [10] with the present EU EV fleet [11], the future European EV fleet composition has been predicted. The development of the composition of the EU EV fleet is shown in Table 6. By 2030 the electrification of the EU fleet is dominated by electric busses which will comprise more than 40 % of the total EU fleet of buses.

The predicted EU27 (The European Union after Britain's exit) fleet is then constructed from the archetypes which have been simulated. Vehicle integrated PV and the efficiency measures outlined earlier can potentially reduce the electricity consumption by the EV fleet. Fig. 17 shows these potential savings if all EVs from April 1, 2024 onwards would be equipped with the economically viable efficiency options and VIPV. The results show that by 2030 with PV on all surfaces there is the potential to save 27 TWh/year in the EU27. And 50 % of these savings come from VIPV.

5. Conclusions

A series of 23 electrical vehicle archetypes have been defined, where an archetype is a combination of a vehicle and a use case. Given the use cases the MEO energy demand model for vehicles was used to quantify the energy required for each archetype and its driving profile. The Energy Flow Model for VIPV has then been applied to each archetype to determine how much energy can be generated by integrated PV and how much this PV energy can contribute to the total energy requirement for the case in question, this is done for two locations, Amsterdam and Madrid.

Results show that the VIPV could contribute up to 80 % of the required energy for passenger cars with low mileage in Madrid. It can generate up to 55 % of the annual energy needs for passenger cars in Amsterdam. Heavier vehicles with high annual mileage see less impact from the VIPV, where for vans it is estimated that VIPV could produce between 15 and 30 %. This drops to 2–4% for busses and long haul trucks. However, due to the high mileage of these vehicles, the impact for the energy grid is still substantial.

To predict the situation in the future, 2025 and 2030, various efficiency improvements in the vehicles were defined and the cost effective ones applied to the use cases. New energy use calculations and VIPV simulations showed that these efficiency improvements and VIPV could reduce the required grid electricity for the EVs.

A prediction of the composition of the future EV fleet in the EU showed that if these efficiency measures were taken as well as VIPV, up to 27 TWh of electricity could be saved by 2030, with VIPV contributing more than 50 % of these savings.

CRediT authorship contribution statement

Anna J. Carr: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Ashish Binani:** Software, Methodology, Investigation. **Akshay Bhoraskar:** Software, Methodology, Formal analysis, Data curation. **Oscar van de Water:** Investigation. **Michiel Zult:** Investigation, Formal analysis, Data curation. **René van Gijlswijk:** Writing – review & editing, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Lenneke H. Slooff:** Writing – review & editing, Writing – original draft, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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