YIELD POTENTIAL OF VEHICLE INTEGRATED PHOTOVOLTAICS ON COMMERCIAL TRUCKS AND VANS

Christoph Kutter, Luis Eduardo Alanis, Dirk Holger Neuhaus, Martin Heinrich
Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 2, 79110 Freiburg, Germany
Corresponding author: Christoph Kutter | Phone: +49 (0)761 4588 2196 | E-mail: christoph.kutter@ise.fraunhofer.de

ABSTRACT: To understand the potential of Vehicle Integrated Photovoltaics (VIPV) on commercial trucks and vans within Europe, we investigate five use cases: A) parcel delivery van, B) rural delivery truck, C) long haul, D) trailer, E) trailer with battery; we consider the European cities of Stockholm, Freiburg and Seville. For this, we first performed a vehicle geometry analysis in which we determined the potential to integrate photovoltaics on typical vehicle types with a module efficiency of 21%. Based on Global Horizontal Irradiance (GHI) datasets and location dependent conversion efficiencies we perform a yield calculation and estimate the final solar yield. A key finding is that the self-consumption during standby charging is a critical parameter in the feasibility of VIPV systems and needs to be minimized. We compute the corresponding annual solar range and find significant potential in the EU for the different use cases: A) 6637 to 11450 km, B) 3084 to 5272 km, C) 4828 to 8173 km, D) 763 to 1424 km, E) 4791 to 8134 km, depending on the city and assumed standby charging losses. Additionally, we perform a break-even analysis and find that irradiation, electricity prices, and the vehicle charging efficiency, are highly critical factors that impact the profitability of VIPV systems. Today VIPV is already profitable in Freiburg and Seville and can achieve payback times of 3,4 years for (B) and (C) in Seville and in Freiburg of 4,0 years for (B) and (C) in Stockholm within 6,9 (B) and 7,0 (C) years when mass production is achieved.

Keywords: VIPV, commercial vehicles, trucks, vans, solar energy, yield, solar range, break even, Lade-PV

1 INTRODUCTION

Vehicle Integrated Photovoltaics (VIPV) potential on trucks has been estimated to 90 GW in the EU [1] but fleet owners are still unsure about the usefulness of VIPV technology besides its ecological benefit. Previous studies have looked at fuel savings of diesel-powered refrigeration trucks using irradiance measurements in the EU, US [2] and yield calculations for Germany [3] and Australia [4]. In this study we expand on the previous findings with updated increased conversion efficiencies [5] and include a discussion of different use cases including the associated losses for power conversion and standby charging, as well as a break even analysis. We aim to provide a deeper study to answer commonly asked questions by fleet owners such as a realistic yield potential estimation or the profitability of VIPV.

Based on current available solar cell efficiencies we will discuss VIPV system sizes for typical commercial truck and van types, and calculate their solar yield for northern, central, and southern Europe. We consider the motion pattern within the yield calculation for five different scenarios: A) parcel delivery van, B) rural delivery truck, C) long haul, D) trailer, E) trailer with battery; to determine the share of solar yield harvested during standby and during driving.

The different application cases are relevant to model the energy flow within the vehicle since in standby mode the high voltage safety infrastructure currently consumes a significant amount of power in standby to allow for charging and power management. Based on typical component efficiencies (e.g. DC PR and converter efficiencies) we estimate the energy conversion flow and calculate the resulting final yield for the different use cases and the respective solar range.

Lastly, we present a break-even analysis for such VIPV systems.

2 METHOD

2.1 Vehicle Analysis

A selection of electric vehicles for commercial transportation of goods, which included different types and weight ratings, was considered for the calculations. Typical truck, van and box body dimensions have been researched and the resulting PV system installed power (P_{STC}) has been computed based on mainstream solar cell concepts. The geometrical data utilized in the study was obtained from brochures or datasheets published by the manufacturers. The roof area used for vans was calculated via geometrical analysis, as seen in Figure 1, while that of trucks and the platform cab, was calculated by using typical box dimensions for the vehicle's type and rating. The energy consumption, when not explicitly provided with reference to Worldwide Harmonised Light Vehicles Test Procedure (WLTP), was calculated with the stated range in km and battery capacity in kWh.

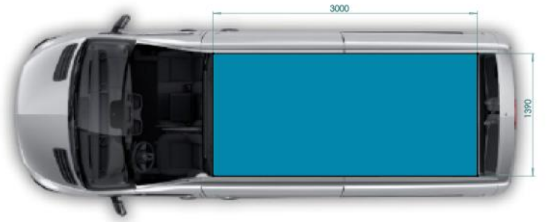

Figure 1. Mercedes-Benz eSprinter roof geometrical analysis [6]

An area usage percentage α_{usage}, which omits parts of the roof non-available for PV (such as framing, etc.), was estimated based on typical framing profiles and for each vehicle type and used to adjust the PV active area. This area was subsequently taken to calculate the potential PV power rating for each vehicle considering a PV module efficiency of 210 W_p/m^2. The vehicle model, type, consumption, roof area, area utilization factor and obtained PV power ratings are shown in Table 1. Vans are usually offered in different lengths and heights, the designation (e.g. L2H2) describes which cabin-size was considered. The highlighted vehicles were selected for the subsequent scenario-based analysis. Figure 2-5 shows illustrative images of these vehicles.

Table 1. PV power installation capacity of selected vehicles based on their roof geometry. Vehicles considered in study appear highlighted with corresponding type of scenario indicated.

Maker	Model	Type	Av. Consumption [kWh/100km]	Roof Area [m²]	Area usage	PV Power [W_p]	Scenario
Renault[7]	Master E-Tech	Van, 3,5t. L3	27,5	11,0	94%	2170	A
Peugeot[8]	e-Boxer	Van, 3,5t. L4H2	18,5	7,3	94%	1440	
Mercedes-Benz[6]	eSprinter	Van, 3,2t. L2H2	30,6	4,1	94%	810	
Fuso[9]	eCanter	Truck, 7,5t.	82,8	15,1	95%	3010	
Volvo[10]	FL Electric	Truck, 16t.	100,0	17,8	96%	3590	
Framo	E-165	Truck, 15t.	100,0	17,8	96%	3590	B
Mercedes-Benz[11]	eActros	Truck, 18t.	120,0	17,8	96%	3590	
MAN[12]	eTGM	Truck, 26t.	97,4	17,8	96%	3590	
Tesla[13]	Semi	Tractor unit + trailer	125,0	34,0	96%	6860	C, D
Freightliner [14]	eCascadia	Tractor unit + trailer	137,5	34,0	96%	6860	
BYD[15]	Q1R	Tractor unit + trailer	217,0	34,0	96%	6860	
ZF[16]	eTrailer	Trailer with battery	125 [see Tesla]	34,0	96%	6860	E

Figure 2. Renault Master E-Tech.
Picture: © 2021 Renault

Figure 3. Framo E-165 with a solar roof
Picture: © 2021 FhG ISE

Figure 4 Tesla Semi
Picture: © 2021 Tesla

Figure 5 ZF eTrailer
Picture: © 2021 ZF

2.2 Vehicle Operation Analysis

When electric vehicles are parked and the ignition is turned off, usually the circuit contactors at the drive train battery are opened and no charging is possible. Therefore, to allow for solar charging, the vehicle needs to be put in an operational state that allows the charging of the high voltage battery. Once the circuit contactors are closed, the safety monitoring infrastructure e.g. Battery Management System (BMS), Vehicle Management System (VMS) needs to be enabled, which leads to standby operational losses L_{CH}.

Hence, we assume that whenever the VIPV output is lower than L_{CH}, the whole system must be shut down to avoid discharging of the battery. The power consumption in fully deactivated state in this case or at night is assumed to be 0W within this study.

To show how significant the effect of the self-consumption is on the VIPV yield and to have a better understanding of how much solar energy is harvested during operation and during standby time of commercial vehicles, we perform a vehicle operation analysis. For this, we defined the hourly driving-to-standby ratio $r_{D2S,i}$ throughout a workday in each scenario and summarized them in Table 2.

We investigate five application scenarios: A) parcel delivery van, B) rural delivery truck, C) long haul, D) trailer, E) trailer with battery with its different charging efficiency.

For Scenario A the Renault Master E-Tech was considered. A 2020 study that looks at the emissions of distribution vehicles in the US found that, during operation, delivery vans can spend more time stationary than in transit when accounting for the minutes utilized on servicing customers; however, this is highly dependent on factors such as distance between customers and depot, service area, roads and parking availability [17]. In this scenario, it was decided to set the driving/standby ratio to 1:1, which would correspond to an urban environment with short transport distances. The working hours were set based on a typical parcel delivery service that operates from 7 AM to 6 PM on weekdays, from 8 AM to 6 PM on Saturdays and does not operate on Sundays. On working days, a 30-minute afternoon break for e.g. driver exchange was noted.

In Scenario B the Framo E-165 is considered. To define the motion profile, real world data from daily operation in Freiburg, Germany was analyzed.

The long-haul profile scenario C was defined according to European regulated steering times as 9 hours per day operation with a 45 min break after 4,5 h of driving [18]. On weekends the long-haul truck is parked and therefore on standby. The Tesla Semi is set as tractor unit. It is assumed that the trailer is always connected to the tractor unit.

For Scenario D and E, trailer and trailer with battery respectively, we analyzed and averaged measured motion data sets from a 2017 study in which the moving patterns of 6 reefer trailers operated in the US and in the EU were observed [2]. In scenario D, it is assumed that the trailer is only connected to the tractor unit while driving, and therefore no energy is harvested in standby mode. Within scenario D the same motion profile for all seven days per week is considered since reefer trailers mostly transport food and are therefore excluded from the driving ban on weekends.

Scenario E considers a trailer equipped with an electric battery. ZF Friedrichshafen AG recently introduced such an electric trailer system [16]. Here we assume that the PV energy can be fully utilized to charge the battery or is fed into the grid when parked over longer time frames.

Table 2. Driving-to-standby ratio per hour of the day in each scenario

	Driving-to-standby ratio $r_{D2S,i}$ per hour of the day											
	A			B			C			D and E		
Hour	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
0-1	0	0	0	0	0	0	0	0	0	0.07	0.07	0.07
1-2	0	0	0	0	0	0	0	0	0	0.06	0.06	0.06
2-3	0	0	0	0.01	0	0	0	0	0	0.06	0.06	0.06
3-4	0	0	0	0.40	0	0	0	0	0	0.05	0.05	0.05
4-5	0	0	0	0.55	0	0	0	0	0	0.05	0.05	0.05
5-6	0	0	0	0.52	0	0	0	0	0	0.05	0.05	0.05
6-7	0	0	0	0.47	0	0	0	0	0	0.08	0.08	0.08
7-8	0.5	0	0	0.38	0	0	1	0	0	0.1	0.1	0.1
8-9	0.5	0.5	0	0.30	0	0	1	0	0	0.13	0.13	0.13
9-10	0.5	0.5	0	0.18	0	0	1	0	0	0.13	0.13	0.13
10-11	0.5	0.5	0	0.33	0	0	1	0	0	0.14	0.14	0.14
11-12	0.25	0.25	0	0	0	0	0.5	0	0	0.15	0.15	0.15
12-13	0.5	0.5	0	0.20	0	0	0.75	0	0	0.17	0.17	0.17
13-14	0.5	0.5	0	0.47	0	0	1	0	0	0.2	0.2	0.2
14-15	0.5	0.5	0	0.35	0	0	1	0	0	0.21	0.21	0.21
15-16	0.5	0.5	0	0.17	0	0	1	0	0	0.2	0.2	0.2
16-17	0.5	0.5	0	0	0	0	1	0	0	0.19	0.19	0.19
17-18	0.5	0.5	0	0	0	0	0.5	0	0	0.16	0.16	0.16
17-19	0	0	0	0	0	0	0	0	0	0.17	0.17	0.17
19-20	0	0	0	0	0	0	0	0	0	0.16	0.16	0.16
20-21	0	0	0	0	0	0	0	0	0	0.14	0.14	0.14
21-22	0	0	0	0	0	0	0	0	0	0.11	0.11	0.11
22-23	0	0	0	0	0	0	0	0	0	0.08	0.08	0.08
23-24	0	0	0	0	0	0	0	0	0	0.08	0.08	0.08

2.3 Yield Calculation

For our estimations, the cities of Stockholm in Sweden, Freiburg im Breisgau in Germany and Seville in Spain were taken as reference for northern, central, and southern Europe, respectively. As Figure 6 illustrates, the expected Global Horizontal Irradiation is highly dependent on the latitude of each location. Plotting the expected GHI over the hours of the year in Figure 7 it becomes clear that the available radiant energy is highly variable throughout the year and, especially in Stockholm, low irradiation is predominant in winter.

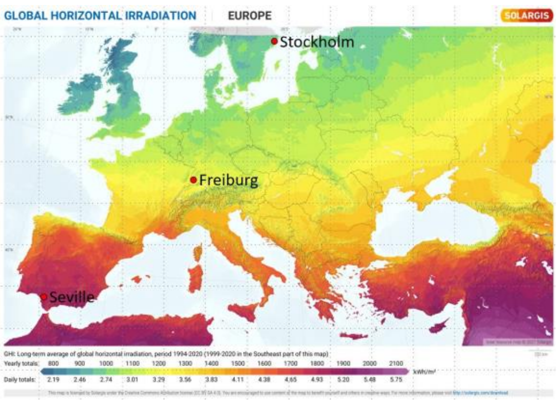

Figure 6. Geolocation of the 3 European cities taken as reference. Source: Solar resource map © 2021 Solargis

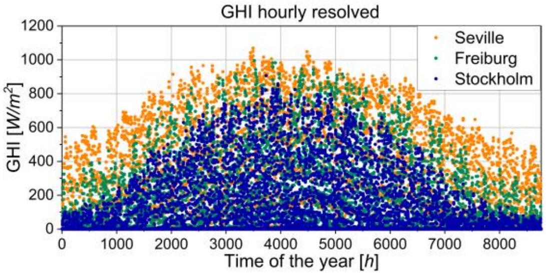

Figure 7. Hourly GHI distribution of given locations [19]

Based on hourly resolved Global Horizontal Irradiance (GHI) data sets from the Meteonorm database [19], the average annual sum of GHI per m² H_G was determined for each city and summarized in Table 3.

Table 3. Average annual horizontal irradiation per m² in given locations obtained from Meteonorm database [19].

Stockholm	Freiburg	Seville
H_G[kWh/m²]		
1,001	1,177	1,813

To assess the yield of photovoltaic systems, the following method based on data is described in [20] and extended for the selected vehicles. Shading is not considered within this study.

The used method translates H_G into a VIPV yield considering the below mentioned vehicle and location dependent parameters and the conversion efficiency within the system.

The DC Performance Ratio $PR_{DC,in}$ of PV systems is a measure for the capture efficiency of the PV array. The generator losses L_C describe the losses till the output of the PV array. For analyzing real world systems, it can be calculated by dividing Array Yield Y_A by the Reference Yield Y_R.

$$PR_{DC,in} = 1 - L_C = \frac{Y_A}{Y_R} \text{ in \%} \quad (1)$$

The Performance Ratio $PR_{DC,out}$, considers conversion losses L_s in the DC-DC converter and cabling between converter and grid, (here intermediate circuit of the vehicle) and is defined by multiplying $PR_{DC,in}$ with a conversion loss factor $(1 - L_s)$. Empirically it can be determined by diving the final yield Y_F by the Reference Yield Y_R.

$$PR_{DC,out} = PR_{DC,in} \cdot (1 - L_s) = \frac{Y_F}{Y_R} \text{ in \%} \quad (2)$$

Figure 8 shows a visualization of the different losses obtained for VIPV.

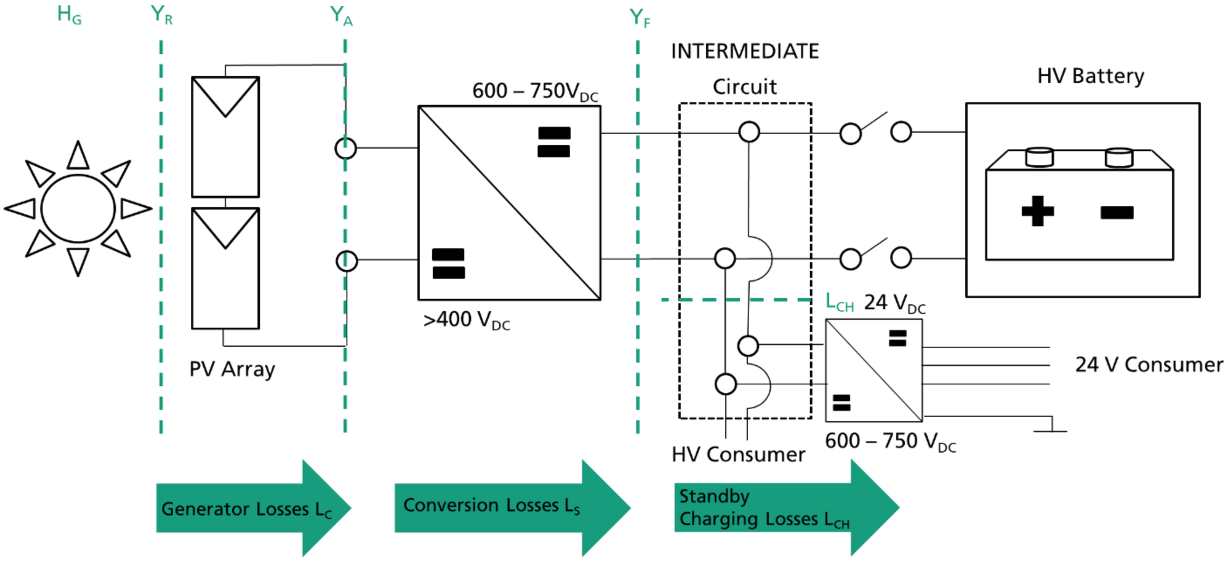

Figure 8. Flowchart showcasing the specific yield of VIPV systems. The array yield Y_A is lower than the reference yield and considers the generator losses L_C. The final yield Y_F is computed for hours driving and standby separately. It takes conversion losses L_S into account and subtracts the standby charging losses L_{CH} by the vehicle in standby charging mode, extended from [20].

Within this study we compute the final yield Y_F for every hour of the year (8760 h/year) while driving as follows:

$$Y_{F,driving} = \sum_{h=1}^{8760} GHI_{location,h} \cdot A_{vehicle} \cdot \alpha_{usage} \cdot \eta_{module} \cdot PR_{DC,out} \cdot r_{D2S,h} \text{ in kWh/year per vehicle} \quad (3)$$

Meanwhile, the share of the final yield harvested in standby is computed according to equation 4. Whenever L_{CH} is higher than the VIPV power the system is assumed to be turned off and therefore yield and consumption set to 0.

$$Y_{F,standby} = \sum_{h=1}^{8760} GHI_{location,h} \cdot A_{vehicle} \cdot \alpha_{usage} \cdot \eta_{module} \cdot PR_{DC,out} \cdot (1 - r_{D2S,h}) - L_{CH} \text{ in kWh/year per vehicle} \quad (4)$$

Hereby vehicle specific areas and area usage factors were taken from Table 1 and η_{module} was set to 21%. The scenario-specific hourly driving-to-standby ratio $r_{D2S,h}$ was taken from Table 2 for every day of the year.
$PR_{DC,in}$ accounts for location-specific factors of the PV array such as operating temperature, which is known to directly affect the performance of photovoltaic systems in such way that a higher PR is expected in colder climates [21].
To account for this effect, $PR_{DC,in}$ was estimated for each location based on data obtained from the Global Solar Atlas 2.0 [22]. Here the calculated specific photovoltaic power output per kWp was divided by the Global Tilted irradiation (GTI) at optimum angle and corrected for system attributed conversion losses as stated in the authors' methodology. The computed $PR_{DC,in}$ values shown in Table 4 consider the following effects:

- Soiling
- Temperature higher than STC
- Mismatch of modules
- Cabling/Ohmic losses

Table 4. DC performance ratio $PR_{DC,in}$ for each location

Stockholm	Freiburg	Seville
	[%]	
90,7	85,4	84,4

The Conversion Losses L_s consider the converter efficiency below 100%, and ohmic losses within the cabling in between the DC-DC converter and the intermediate circuit and are set to 2% referring to similar sized residential inverters [23].
For the standby operational demand L_{CH}, we performed measurements on the Framo E-165 truck, which reveal a standby consumption of up to 700 W when the ignition is on, which is in good accordance with literature [24].
On the other hand, a study evaluating the efficiency of photovoltaic home storage systems found the standby power consumption of such systems to vary between 0 and 40.8 W for a full battery and 0.1 W and 46.2 W with an empty battery [25].
Although vehicle and home storage systems concepts cannot be directly compared, the study reveals that storing PV energy can generally be done more efficiently. With this as reference, we take a self-consumption value of 25 W as a benchmark.
To illustrate the impact of the standby operational demand L_{CH} on the solar yield, we perform a sensitivity analysis considering an L_{CH} value of 0, 25, 100 and 700 W.
It is clear, however, that in future electric vehicles featuring a VIPV system, a new operation mode for "standby solar charging" will need to be implemented in the VMS, its purpose being to minimize the energy demand for charging readiness by deactivating all unnecessary consumers.

2.4 . Solar range calculation

The solar range was computed based on the average power consumption. This specification, which is vehicle-dependent, is based on the WLTP and was taken or

calculated from the advertised technical data offered by the manufacturers (see Table 1).
For electric vehicles it is typical to find this figure expressed in the units kWh/100km. With this, the solar range extension can be calculated in km per year by dividing the annual VIPV yield by the average consumption and multiplying it by a factor of 100.
It must be noted that the average consumption is highly variable from model to model and only vaguely correlates to the vehicle type, size, and weight rating. This may also imply that power efficiency of electric vehicles can still be optimized as the technology becomes more mature for trucks.

2.5 Break Even analysis for Scenario B and C

Further, we perform an Levelized Cost of Electricity (LCOE) analysis [26, 27] for a purchased VIPV system and perform a break-even analysis from the customer perspective for Scenario B and C with 25 W operational losses L_{CH} in standby and with the assumption of the parameters as shown in Table 5 taken for small scale rooftop systems from [27]. Yearly degradation was set to 1% as we expect it to be higher than within conventional modules (typically 0,25%/a) and lifetime was set to 10 years [1].

Table 5. Economic input parameters

$WACC_{,real}$ (Weighted Average Cost of Capital) in % [27]	2,2
Lifetime in years	10
Degradation in % per year	1

Within the break-even analysis every kWh utilized from the VIPV system replaces a kWh bought from the grid. We consider country specific household electricity prices as stated in Table 6. Charging fees at public (fast) charging stations are often even higher than household prices while non-household electricity prices e.g. at the home depot could also be lower.

Table 6. Household - electricity prices at each location [28]

Stockholm	Freiburg	Seville
	€/kWh	
0,17	0,3	0,23

The cost parameter in Table 7 indicates VIPV component prices of the prototype phase. These prices are conservative and likely to decrease with ramp up on mass production of VIPV components. Therefore, we also provide an outlook scenario with system prices of 1,0 €/Wp.

Table 7. System-related input parameters

Module price in €/Wp	0,5
Power Electronics in €/Wp	0,4
Safety Accessories in €/Wp	0,3
Installation in €/Wp	0,5
System Price in €/Wp	1,7 (or 1,0)

3 RESULTS

3.1 VIPV system size for commercial vehicles

Since the power potential of a VIPV system (or of any solar-energy-based system) depends on the surface available for catching sunlight, it was possible to estimate the maximum installed power on different vehicle types based on their roof geometry.
We find that box-bodies and trailers are usually built on dimensions that are largely standardized, featuring a typical roof area of 17.8 m^2 and 34 m^2, respectively, equivalent to approximately 3590 W_p and 6860 W_p of installed PV power considering a module performance of 210 W_p/m^2 (in line with current cell and module technologies) and an area utilization factor (α_{usage}) of 96%. On the other hand, utility vans come in a wide range of sizes and designs, so the potential for VIPV installed power varies likewise. Due to the smaller roof surface and increased geometrical complexity, the area utilization factor (α_{usage}) used for vans was set to 94%.
We find that within the sampled utility vans, the roof areas observed range between 4,1 m^2 and 11 m^2, equivalent to a maximum installed PV power of 810 W_p and 2170 W_p, respectively.

3.2 Reference VIPV yield and solar range

The solar yield and range were calculated for the sampled vehicles in the different scenarios detailed in 2.2 considering the location-based inputs explained in 2.3.
Within the assumptions made for the expected system characteristics and taking standby operational losses L_{CH} of 25 W as reference, we find that the expected annual solar yield for the studied vehicles and scenarios would be within the range of 1825 kWh (for a Renault Master E-Tech utility van in scenario A in Stockholm) and 10216 kWh (for a Tesla Semi tractor unit with an attached trailer, operated under scenario C in Seville).
These yields would translate to an annual solar range equivalent to 6637 km and 8173 km, respectively. The overview of all studied scenarios and cities can be found in Figure 9. As Table 8 summarizes, the VIPV system can cover significant shares of the energy demand of the vehicle assuming German average annual mileage for each vehicle type: Up to 35% in Scenario A, up to 14% in Scenario B and up to 9% for long-haul trucks in C and E.

Table 8. Solar ranges, average annual mileage, and solar coverage for each scenario

	location	Solar Range for L_{CH} 25 W [km]	German average annual milage 2020 [km] [29]	Solar coverage [%]
A	Stockholm	6637	Van ≤ 3,5t: 19.038	35
	Freiburg	7397		39
	Seville	11450		60
B	Stockholm	3084	Truck >7,5t: 35.757	9
	Freiburg	3429		10
	Seville	5272		15
C	Stockholm	4828	Tractor Unit: 89.667	5
	Freiburg	5356		6
	Seville	8173		9
E	Stockholm	4791		5
	Freiburg	5317		6
	Seville	8134		9

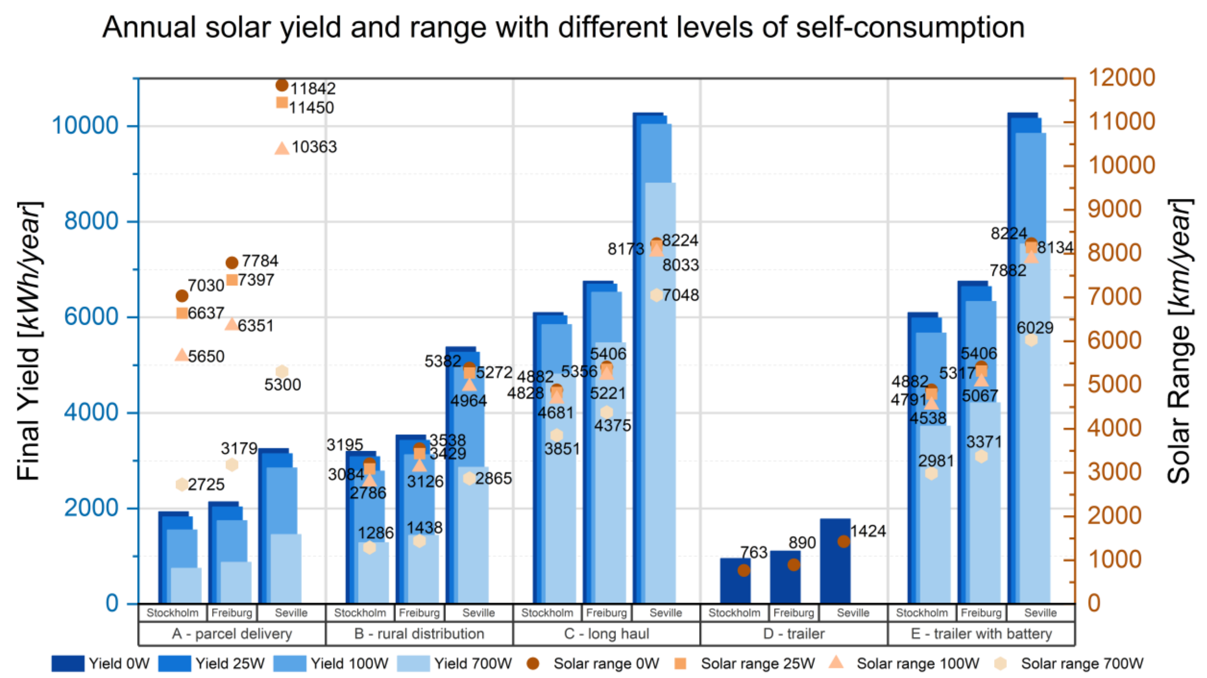

Figure 9 Results of VIPV yield and solar range calculation for Scenarios A to E and all 3 locations and varying L_{CH}

3.3 Sensitivity analysis for self-consumption

As discussed in the method section, the self-consumption of the VIPV system in standby mode plays a central role in the final solar yield and range.

For this reason, we perform a sensitivity analysis on the abovementioned calculations considering a self-consumption of 0 W (VIPV yield upper limit), of 700 W (level observed in the Framo demonstrator truck) and of 100 W; and compare them with the reference potential (25 W self-consumption) from 3.2.

Table 9 summarizes the share of the potential VIPV energy that is self-consumed in each scenario.

Since scenario D already considers that energy storage is not viable, it was excluded from the sensitivity analysis.

We find that the standby operational losses L_{CH} minimize the VIPV Yield significantly, especially for smaller vehicles and slightly more at northern locations.

Long haul trucks benefit from long operation hours and large systems so that self-consumption is lower. It becomes evident that the charging process in standby for traction batteries needs to be optimized.

Table 9. Share of VIPV energy self-consumed for varying levels of standby self-consumption

Relative standby operational losses [%]					
Scenario	L_{CH} [W] →	0	25	100	700
A	Stockholm	0	6	20	61
	Freiburg	0	5	18	59
	Seville	0	3	12	55
B	Stockholm	0	3	13	60
	Freiburg	0	3	12	59
	Seville	0	2	8	47
C	Stockholm	0	1	4	21
	Freiburg	0	1	3	19
	Seville	0	1	2	14
E	Stockholm	0	2	n/a	n/a
	Freiburg	0	2	n/a	n/a
	Seville	0	1	n/a	n/a

3.4 Break Even Analysis for VIPV Scenario B and C

In this analysis we compare the yearly yield by solar irradiation in terms of charging cost savings to the initial cost of the system as shown in Section 2.5. We find the VIPV system can be profitable in Freiburg and Seville within Scenarios B (Table 10) and C (Table 11) assuming a 10-year lifetime. In Stockholm the VIPV system is only profitable within 10 years if the system cost reaches 1,0 €/Wp and below.

The LCOE per kWh of the VIPV System are always lower than a kWh bought from the grid as a consumer in Germany and Spain. With current conservative system cost and household prices, the VIPV system reaches break-even after 6,8 years in (B) and (C) in Freiburg. The net present value (NPV) ranges from 1976 € in (B) to 3639 € (C) in Freiburg.

Table 10. Results of Break-Even-Analysis for Scenario E

	Stockholm		Freiburg		Seville	
System cost [€/Wp]	1,7	1	1,7	1	1,7	1
Break even [years]	11,8	6,9	6,8	4,0	5,8	3,4
Net present value 10 years [€]	-1478	1035	1976	4489	3320	5833
LCOE (10 years) [€/kWh]	0,22	0,13	0,20	0,12	0,13	0,08

When we consider mass production of VIPV components and prices in the range of small scale roof top systems ~1,0 €/Wp according to [5] we find much lower payback times of 3,4 years in (B) and (C) in Seville and in Freiburg of 4,0 years in (B) and (C), and VIPV to be profitable in Stockholm within 6,9 (B) and 7,0 (C) years lifetime in Scenario B and C, respectively, as shown in Table 11 and Figure 10. The LCOE drops accordingly, whereas NPV increases.

Table 11. Results of Break-Even Analysis for Scenario C

	Stockholm		Freiburg		Seville	
System cost [€/Wp]	1,7	1	1,7	1	1,7	1
Break even [years]	11,9	7,0	6,8	4,0	5,8	3,4
Net present value 10 years [€]	-2916	1882	3639	8437	6236	11033
LCOE (10 years) [€/kWh]	0,23	0,13	0,20	0,13	0,13	0,08

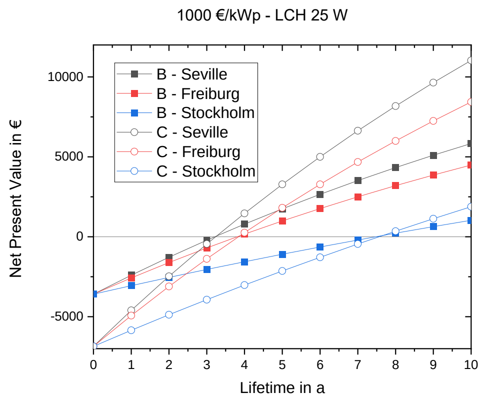

Figure 10 Break-even analysis over ten years lifetime for a Framo-E165 VIPV-System with 1,0 €/Wp system cost

The combination of low irradiation and cheap electricity is responsible for longer payback times of the VIPV system in the investigated scenarios in Sweden. For Germany, although the VIPV yield is lower on commercial vehicles, it is only slightly less profitable than in Spain due to the higher electricity price. Payback times below 5 years in Germany and Spain are realistic.

4 CONCLUSION

Based on the geometry of different electric commercial vehicles and their predicted operation patterns under specific scenarios in three European cities, we analyzed the critical variables for implementing VIPV systems that are technically and economically viable. Our main conclusions are described below.

4.1 Solar yield and range extension

VIPV installed only on the roof of the electric vehicle covers a significant part of the energy consumption of commercial vehicles within all investigated scenarios. Considering an optimized system efficiency, the following annual solar ranges can be obtained in Stockholm and Seville. The value in % states the VIPV coverage of the estimated annual energy demand of the vehicle:

- A - Parcel Delivery Vans: 6637 to 11450 km/year, solar energy coverage 35 to 60%
- B – Rural Delivery Trucks: 3084 to 5272 km/year, solar energy coverage 9 to 15%
- C – Long Haul Truck 4828 to 8173 km/year, solar energy coverage 5 to 9%
- D – Trailer (only harvesting while driving) 763 to 1424 km/year, solar energy coverage 0.9 to 1.6%
- E – Trailer with battery/grid feed-in 4791 to 8134 km/year, solar energy coverage 5 to 9%

4.2 VIPV can be economically feasible

VIPV on commercial vehicles is profitable in central and southern Europe when assuming a ten-year lifetime and current technologies and respective costs are reached. Irradiation and electricity prices and the vehicle charging efficiency have significant impact on the feasibility of VIPV systems.
We find the payback period in Scenario B and C for rural distribution and long-haul trucks to range from 3,4 years in Seville, to 4,0 years in Freiburg and 6,9 to 7,0 years in Stockholm, assuming mass production with cost of 1 €/Wp.
Additionally, VIPV features emission free energy onboard, and a gain in comfort through location independent charging and less and shorter charging stops.

4.3 Standby operational losses and the need for efficient solar charging

We found that one of the main factors to consider is the energy that the system itself must consume for tasks such as the safety monitoring of the high voltage battery charge when parked (i.e. standby) or while driving.
The analysis of the operation patterns show that the solar irradiation perceived during standby time is more significant than when driving, therefore it is critical that the standby operational losses are minimized from a system perspective.
As an example, we find that a standby self-consumption comparable to that of a residential system (25 W) would lead to operational losses of only 3% of the annual solar yield for scenario B in Stockholm, while a high level of self-consumption (700 W) would increase the losses up to 60% under the same circumstances.
To reach economic feasibility, it is necessary to review and optimize the energy flow and vehicle management system and minimize the self-consumption of the system during charging in standby.
Further, the system needs the capability to check if enough solar power is available when the vehicle is turned off. This could be achieved by using irradiation sensors or vehicle location dependent sun height calculations, to avoid waking up at night times.

5 OUTLOOK

We expect the use case VIPV to become even more feasible for the end user over time.
Firstly, with an historic efficiency increase of mainstream c-Si PV of 0,6 $\%_{abs}$ per year, the solar yield per vehicle will increase. Secondly, mass production of (VI)PV components will lead to cheaper LCOE. Every time the global, cumulative PV module production doubled in the last 40 years, the module selling price went down by 25% [5] and we expect that this trend will continue in the future. Thirdly, grid tied electricity prices tend to rise over time, which will increase the savings for each kWh produced by a VIPV system. Fourthly, the power supply on the vehicle may reduce charging times during operation of the vehicle. Finally, VIPV will benefit from more efficient electric vehicle drive trains in the future. To further boost the solar range of VIPV systems, additional areas on the commercial vehicles e.g. the sides of the box body, the cabin roof or the hood could be utilized.

6 ACKNOWLEDGEMENT

We thank Torsten Peppel, Ralf Noeske and Steffen Margenberg, from M&P Motion Control and Power Electronics GmbH, Dr. Aswin Linsenmeyer from SUNSET Energietechnik GmbH and Rolf Huhn from TBV Kühlfahrzeuge GmbH for exceptional good collaboration within the project "Lade-PV" and guidance on current component prices. Finally, we would like to thank the German Ministry of Economic Affairs and Energy (FKZ 03EE1002A "Lade-PV") for their funding.

REFERENCES

[1] C. Kutter, F. Basler, D. H. Neuhaus, M. Heinrich, J. Markert, and L. E. Alanis, "Integrated Lightweight, Glass-Free PV Module Technology for Box Bodies of Commercial Trucks," 37th European Photovoltaic Solar Energy Conference and Exhibition, pp. 1711–1718, 2020, doi: 10.4229/EUPVSEC20202020-6DO.11.6.

[2] U. Eitner et al., "Solar Potential on Commerical Trucks: Results of an Irradiance Measurement Campaign on 6 Trucks in Europe and USA," in Proceedings of the 33rd European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC), Amsterdam, Netherlands, 2017, pp. 2147–2150.

[3] M. Kühnel, B. Hanke, S. Geißendörfer, K. von Maydell, and C. Agert, "Energy Forecast for Mobile Photovoltaic Systems with Focus on Trucks for Cooling Applications," 2016, doi: 10.4229/EUPVSEC20162016-6EO.1.6.

[4] B. Elliston and M. Dennis, "Feasibility of Solar-Assisted Refrigerator Transport in Australia," Australian National University, Department of Engineering, Canberra, 2009.

[5] Fraunhofer Institute for Solar Energy Systems ISE with support of PSE Projects GmbH, Ed., "PHOTOVOLTAICS REPORT 27.06.21," Accessed: 30.08.21. [Online]. Available: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

[6] Mercedes-Benz AG, The Mercedes-Benz eSprinter. [Online]. Available: https://www.mercedes-benz.co.uk/vans/content/dam/vans/united-kingdom/brochures/december2020/https://www.mercedes-benz.co.uk/vans/en/e-sprinter-panel-van (accessed: Oct. 2 2021).

[7] Renault, New MASTER Z.E.: Dimensions. [Online]. Available: https://www.renault.co.uk/electric-vehicles/master-ze/specifications.html?bodyTypeCode=PT1261_platform_cab (accessed: Nov. 2 2021).

[8] Peugeot, Peugeot Boxer: Prices, equipment & technical specification. [Online]. Available: https://media-ct-ndp.peugeot.com/file/99/2/peugeot-boxer-spec-sheet-january-2018-web.pdf?lcdv16=2PU91DHDP670A0C0 (accessed: Nov. 2 2021).

[9] Daimler AG, FUSO eCanter. [Online]. Available: https://media.daimler.com/marsMediaSite/ko/en/45600295 (accessed: Nov. 2 2021).

[10] Volvo Truck Corporation, "Electromobility Made Easy: Electrified Urban Transport by Volvo Trucks," [Online]. Available: https://www.volvotrucks.com/en-en/trucks/alternative-fuels/electric-trucks.html

[11] Mercedes-Benz AG, Mercedes-Benz eActros: Sustainable, fully electric and quiet. [Online]. Available: https://www.mercedes-benz.com/en/vehicles/trucks/mercedes-benz-eactros-sustainable-fully-electric-and-quiet/ (accessed: Nov. 2 2021).

[12] MAN Truck & Bus SE, Fully Electric, Whisper-Quiet and Highly Efficient: The MAN eTGM. [Online]. Available: https://www.man.eu/de/en/truck/models/man-etgm/etgm.html (accessed: Nov. 2 2021).

[13] I. Tesla, Tesla Semi: Product website. [Online]. Available: https://www.tesla.com/semi (accessed: 18.08.20).

[14] Daimler AG, Electrified on the highway, Freightliner eCascadia and eM2. [Online]. Available: https://www.daimler.com/sustainability/climate/ecascadia.html (accessed: Nov. 2 2021).

[15] BYD Company Limited, Q1R. [Online]. Available: https://sg.byd.com/wp-content/uploads/2017/11/Q1R_SPEC.pdf (accessed: Nov. 2 2021).

[16] Frank Discher, Ausgezeichnet: umweltfreundlicher eTrailer von ZF erhält CLEPA-Innovationspreis 2020, 26.11.20. Accessed: 18.08.21. [Online]. Available: https://press.zf.com/press/de/releases/release_21889.html

[17] M. Figliozzi, J. Saenz, and J. Faulin, "Minimization of urban freight distribution lifecycle CO2e emissions: Results from an optimization model and a real-world case study," Transport Policy, vol. 86, pp. 60–68, 2020, doi: 10.1016/j.tranpol.2018.06.010.

[18] REGULATION (EC) No 561/2006 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the harmonisation of certain social legislation relating to road transport and amending Council Regulations (EEC) No 3821/85 and (EC) No 2135/98 and repealing Council Regulation (EEC) No 3820/85. Accessed: 18.08.21. [Online]. Available: https://eur-lex.europa.eu/resource.html?uri=cellar:5cf5ebde-d494-40eb-86a7-2131294ccbd9.0005.02/DOC_1&format=PDF

[19] J. Remund, S. C. Müller, M. Schmutz, and P. Graf, "Meteonorm Version 8," 2020, doi: 10.4229/EUPVSEC20202020-5BV.3.8.

[20] K. Mertens, Photovoltaics: Fundamentals, Technology and Practice. New Jersey: Wiley, 2014.

[21] J. Leloux, J. Taylor, R. Moreton Villagrá, L. Narvarte, D. Trebosc, and A. Desportes, "Monitoring 30,000 PV Systems in Europe: Performance, Faults, and State of the Art," 2015, doi: 10.4229/EUPVSEC20152015-5AO.8.1.

[22] Solargis s.r.o, Global Solar Atlas 2.0: a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). [Online]. Available: https://globalsolaratlas.info./ (accessed: 18.08.21).

[23] Sungrow Power Supply Co. Ltd, Technical Datasheet SG3K/3K6/4K/4K6/5K/6K-D:

Residential String Inverter. [Online]. Available: https://en.sungrowpower.com/upload/documentFile/DS_SG3K%203K6%204K%204K6%205K%206K-D%20Datasheet(EMEA)_V12_EN.pdf.pdf (accessed: 30.08.21).

[24] C. Lodi, A. Seitsonen, E. Paffumi, M. de Gennaro, T. Huld, and S. Malfettani, “Reducing CO 2 emissions of conventional fuel cars by vehicle photovoltaic roofs,” Transportation Research Part D: Transport and Environment, vol. 59, pp. 313–324, 2018, doi: 10.1016/j.trd.2018.01.020.

[25] N. Munzke, B. Schwarz, F. Büchle, and M. Hiller, “Evaluation of the efficiency and resulting electrical and economic losses of photovoltaic home storage systems,” Journal of Energy Storage, vol. 33, p. 101724, 2021, doi: 10.1016/j.est.2020.101724.

[26] P. Konstantin, Praxisbuch Energiewirtschaft: Energieumwandlung, -transport und -beschaffung, Übertragungsnetzausbau und Kernenergieausstieg, 4th ed. Berlin: Springer Vieweg, 2017. [Online]. Available: http://www.springer.com/

[27] C. Kost, S. Shammugam, V. Fluri, D. Peper, A.D. Memar, T. Schlegl, “Levelized cost of electricity renewalbe energy technologies: June 2021,” Jun. 2021. Accessed: 26.08.21. [Online]. Available: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2021_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf

[28] eurostat, “Electricity prices (including taxes) for household consumers, second half 2020,” Accessed: 26.08.21. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics

[29] F. Kraftfahrt-Bundesamt, Ed., “Verkehr in Kilometern 2020 - Inländerfahrleistung: Entwicklung der Fahrleistungen nach Fahrzeugarten seit 2016,” Accessed: 30.08.21. [Online]. Available: https://www.kba.de/DE/Statistik/Kraftverkehr/VerkehrKilometer/vk_inlaenderfahrleistung/vk_zum_herunterladen/verkehr_in_kilometern_kurzbericht_pdf.pdf?__blob=publicationFile&v=5