

Environmental Impacts of Integrated Photovoltaic Modules in Light Utility Electric Vehicles

Olga Kanz ^{1,*}, Angèle Reinders ², Johanna May ³ and Kaining Ding ¹

¹ IEK-5 Photovoltaik, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany; k.ding@fz-juelich.de

² Energy Technology Group, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands; a.h.m.e.reinders@tue.nl

³ Cologne University of Applied Sciences, Institute of Electrical Power Engineering (IET), 50678 Cologne, Germany; johanna.may@th-koeln.de

* Correspondence: o.kanz@fz-juelich.de; Tel.: +49-2461-61-1636

Received: 20 August 2020; Accepted: 29 September 2020; Published: 1 October 2020

Abstract: This paper presents a life cycle assessment (LCA) of photovoltaic (PV) solar modules which have been integrated into electric vehicle applications, also called vehicle integrated photovoltaics (VIPV). The LCA was executed by means of GaBi LCA software with Ecoinvent v2.2 as a background database, with a focus on the global warming potential (GWP). A light utility electric vehicle (LUV) named StreetScooter Work L, with a PV array of 930 Wp, was analyzed for the location of Cologne, Germany. An operation time of 8 years and an average shadowing factor of 30% were assumed. The functional unit of this LCA is 1 kWh of generated PV electricity on-board, for which an emission factor of 0.357 kg CO₂-eq/kWh was calculated, whereas the average grid emissions would be 0.435 kg CO₂-eq/kWh. Hence, charging by PV power hence causes lower emissions than charging an EV by the grid. The study further shows how changes in the shadowing factor, operation time, and other aspects affect vehicle's emissions. The ecological benefit of charging by PV modules as compared to grid charging is negated when the shadowing factor exceeds 40% and hence exceeds emissions of 0.435 kg CO₂-eq/kWh. However, if the operation time of a vehicle with integrated PV is prolonged to 12 years, emissions of the functional unit go down to 0.221 kg CO₂-eq/kWh. It is relevant to point out that the outcomes of the LCA study strongly depend on the location of use of the vehicle, the annual irradiation, and the carbon footprint of the grid on that location.

Keywords: life cycle assessment; CO₂ emissions; photovoltaic systems; electric vehicles; VIPV

1. Introduction

The European Union (EU) has agreed on a range of policies aiming to reduce greenhouse gas emissions in various sectors of society. Since transport largely contributes to these emissions by a share of 27% of the EU's total emissions in 2016, these emissions have to be reduced. For the year 2030, this policy implies that in the EU fleet-wide CO₂ emissions of passenger cars should be reduced by 37.5% as compared to 1990 levels. For new vans and trucks, the emissions should be reduced by 31% [1]. Therefore, new strict targets require the reduction of average CO₂ emissions of new vehicles that will enter the market. Consequently, the year 2020 is widely expected to bring dramatic changes to the automotive market. Due to the aforementioned targets, manufacturers are forced to invest intensively in innovative technologies of sustainable mobility. Therefore, many automotive players focus on battery electric vehicles (BEVs). In recent years, a large number of environmental impact studies were published, analyzing the potential environmental benefits of electric vehicles (EVs). The overall conclusion is that BEVs are preferable over petrol and diesel vehicles, however only if charged

by renewable energy [2]. A possible solution is to charge these cars with low-emission renewable energy technologies such as photovoltaic systems. This could be achieved by charging stations which are powered by PV systems or by photovoltaic solar modules which are built in a car's body parts, also called vehicle integrated photovoltaics (VIPV). Some vehicle manufacturers already aim at integrating PV cells in body parts of their passenger cars. One of the most recent solar powered electric vehicles is the Lightyear One of the Dutch company Lightyear. The vehicle has an integrated silicon PV array of more than 5 m² with a nominal installed power of 1250 Wp. Similarly, Munich-based producer Sono Motors is planning on launching their solar electric vehicle, named Sion. The Sion's PV array has a nominal power of 1200 Wp. Solar charging in summer can add 34 km to the drive range of 255 km. With Audi's e-tron Quattro with a nominal PV power of 400 Wp and the Toyota Prius P with a PV array of 860 Wp, two of the car industry's major players recently entered the market as well. Especially for light utility electric vehicles (LUV), VIPV could be an attractive feature due to their predictability of utilization, in particular their moments of use and daily travel distances, and their significantly larger and flat roof surface which, if covered by solar cells, can potentially yield sufficient amounts of solar power. LUVs are usually vehicles with a gross vehicle weight of no more than 3.5 metric tonnes and are optimized to be tough-built, have low operating costs, and to be used in intra-city operations. Though prior studies have often indicated that VIPV will result in lower CO₂ emissions, actual life cycle assessments (LCAs) of VIPV are barely available, and most claims until now have not been quantified or validated for the specific situation of VIPV of LUVs [3–5]. Thus, the goal of this work is to analyze how PV-powered vehicles can contribute to sustainable mobility. Therefore, an LCA focused on determining the CO₂ emissions of a German VIPV LUV called StreetScooter will be conducted. The results of this research could be useful for car manufacturers, to calculate emissions per vehicle, for political institutions to estimate environmental impacts for the transport sector, and for business parties in the solar market to identify further application possibilities and yield useful data to identify critical areas for the improvement of VIPV for LUVs.

This LCA study was executed in the framework of a project called STREET, which was funded by the German Ministry for Economic Affairs and Energy and a German logistics company of Deutsche Post DHL Group named StreetScooter, which is currently working on the integration of PV on electric light utility vehicles (see Figure 1). Forschungszentrum Jülich as an organization for applied research supports the project by equipping the vehicle with PV modules and by analyzing the energy yield of PV modules on this vehicle by the analysis of data measured by radiation sensors on the vehicle under real shading and reflection conditions.



Figure 1. StreetScooter Work L Reprinted from: CC-BY-SA-4.0 (via Wikimedia Commons), Superbass, 2017.

This paper is structured as following: in Section 2 the LCA method will be explained and all input parameters of the LCA will be described. Major assumptions regarding the operation phase

and technology choice for the on-board vehicle application are discussed. The results, sensitivity analyses, and limitations of the study are reported in Section 3. Finally, Section 4 summarizes the results, presents the conclusions, and offers recommendations for future studies.

2. Method and Data

This section presents the general methodology used to execute the LCA, defines the efficiency of the VIPV investigated, and quantifies the resulting CO₂ emissions. Additionally, key parameters that limit the environmental performance of the electricity produced by the PV system integrated into the vehicle are shown. Assumptions about these critical parameters for the reference case are clarified.

2.1. Life Cycle Assessment Method

LCA is a useful tool to quantify environmental performance, considering a holistic perspective. LCA is generally understood as a compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle [6]. LCA studies always consist of four main phases, which are covered through ISO standards (DIN 14044; ISO 14040:2006). The first step of the LCA is used to define the goal and scope of the study. The second step is a life cycle inventory (LCI) model through which data is collected and organized. The third step is the life cycle impact assessment (LCIA), used to understand the relevance of all the inputs and outputs in an environmental framework. The fourth step is the interpretation, which is a systematic technique to identify, check, and evaluate information resulting from the LCIA (see Figure 2).

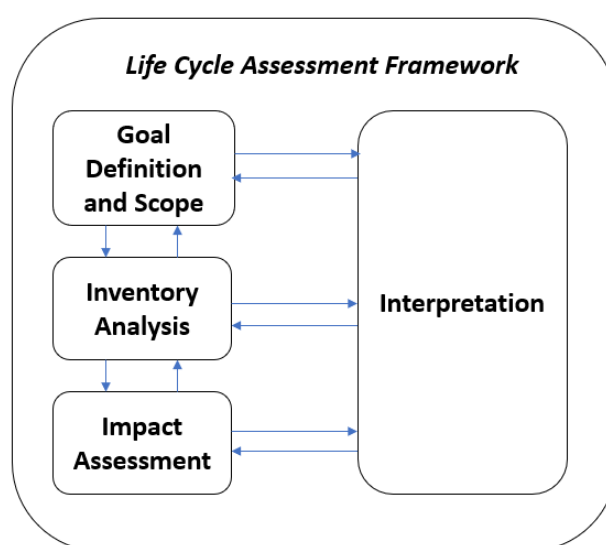


Figure 2. Life cycle assessment (LCA) framework (DIN 14044; ISO 14040:2006).

The environmental impact assessment for this study is completed at the mid-point level. Midpoints are considered to be connections in the cause–effect chain of different impact categories, also known as the problem-oriented approach or classical impact assessment method. Greenhouse gas emissions (kgCO₂-eq) were used as an indicator of climate change contribution. The 100-year global warming potentials based on the latest IPCC 2013 were assumed, according to their radiative, forcing capacity relative to the reference substance CO₂. Global warming potential (GWP) during the life cycle stages of a PV system was estimated as an equivalent of CO₂ containing all the significant emissions CO₂ (GWP = 1), CH₄ (GWP = 25), N₂O (GWP = 298) and chlorofluorocarbons (GWP = 4750–14,400). The calculations were performed using LCA software GaBi with Ecoinvent v2.2+ as background database. GaBi is a process-oriented software, examining the material and energy flows of each step of the production chain. The applied methodology of this study can be divided into four sections which will be briefly described below.

(A) VIPV Use Case Parameters

In the first section, the system boundaries and the input parameters for the operation in urban delivery were clarified and collected for the Use Case StreetScooter. Promising VIPV configuration was defined as the result.

(B) LCI of VIPV—Manufacturing

The second section was dedicated to compiling an inventory of energy and material inputs and outputs over the life cycle of VIPV. Life-Cycle Inventory was completed based on the data from literature. Based on the Inventory, a GaBi model was developed.

(C) LCI of VIPV—Operation and VIPV Energy flow model

The third part included the simulation of VIPV contribution to charging. To simulate the reduction of grid power demand, an energy flow model for the identified reference case was developed.

(D) Evaluation of environmental impacts

In the last part, potential environmental impacts (GWP) related to identified inputs and releases were evaluated. LCA results were compared to grid charging by means of their environmental impacts. The characterization factors were based on IPCC (2013) and should be incorporated for the impact category of global warming potential, which is tracked in kg CO₂ eq.

2.2. Functional Unit, Goal, and Scope

The use case is the light utility battery electric vehicle Work L of StreetScooter. The functional unit for this study is 1 kWh of electricity supplied by the PV system to the battery of the StreetScooter. In comparison to the functional unit of 1 km driven, the emissions of 1 kWh can be calculated more accurately. Furthermore, the chosen functional unit of 1 kWh allows for a direct comparison of effects of charging by PV modules to those due to charging by the grid. Thus, the emissions of VIPV and grid charged BEV can be evaluated more precisely referring to the same functional unit. The operation of the electrical vehicle is set in Cologne, Germany and starts in 2017. Within the scope of this project, the environmental impacts of VIPV are to be studied according to the standard of life cycle assessment ISO 14040:2006. The PV system configuration is based on the first generation of the VIPV panels for the STREET Project with heterojunction silicon PV modules manufactured in China. The analyzed VIPV configuration includes three panels and three control units including the cables mounted on the vehicle roof. The overall capacity of the VIPV system is 930 Wp. The system of the VIPV electricity includes raw material extraction, wafers, crystalline silicon-based heterojunction solar cells and module manufacturing, mounting structures manufacturing, inverters manufacturing, system installation, and the operation.

2.3. Input Parameters for the Life Cycle Inventory

The production process of a typical commercial crystalline silicon solar cell is modelled based on the existing datasets describing the supply chain [7] (see Figure 3). Input parameters of the manufacturing of the PV control unit (PVCU) as well as the vehicle integration process were added based on internal communication in the project STREET. The electricity consumption on all process levels is modelled following specific electricity mixes corresponding to China (CN) or Germany (DE), respectively, based on the Ecoinvent datasets.

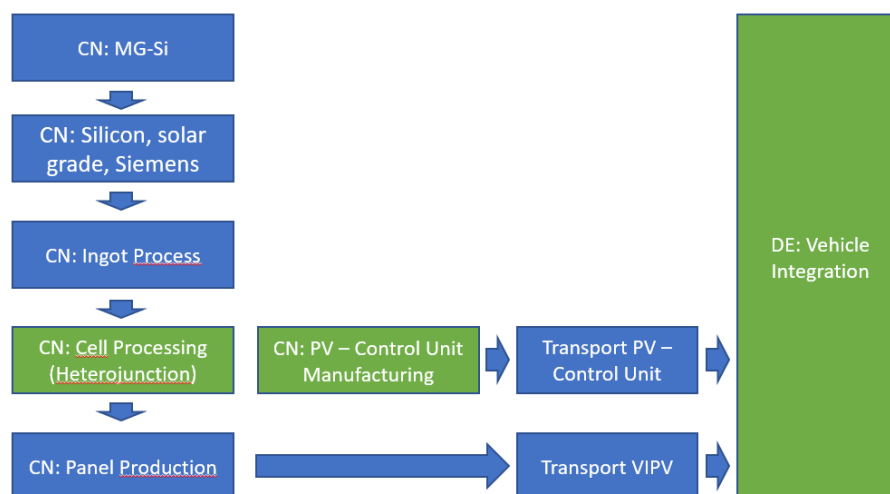


Figure 3. Vehicle integrated photovoltaics (VIPV) system value chain: process flow diagram. CN means China, DE Germany.

All input parameters of the manufacturing and vehicle integration process are described in Table 1. The exact location of manufacturing plants is undocumented and unknown. However, it can be assumed that the location of these plants is somewhere within China. Modelling of the transportation was based on the standard distances as suggested in the Guideline for PC LCA [7]. Metal parts were commonly reported with 200 km train and 100 km truck transportation in China. Additionally, transoceanic transport from China to Belgium was estimated to be 19,994 km based on searates.com data. In Europe, lorry transport from Antwerp (Belgium) to Cologne (Germany), a total of 500 km, was used.

Table 1. Input parameters of the manufacturing process and vehicle integration Pprocess.

Parameter		Based on	Comment
Wafer	Type: n-type c-Si	(b)	Wafer (Solar Grade)
	Thickness: 180 nm	(a)	Wafer thickness
Cell	Technology SHJ c-Si		SHJ cell processing adopted due to STREET requirements, $\mu\text{c-SiOx:H}$
	Area: 239 mm ²	(a)	156 × 156 mm ²
	Efficiency: 22.5%	(c)	Describes the efficiency of the solar cells
Panel	Efficiency: 19.7%	(c)	Describes the efficiency of the solar cells
	Glass thickness: 2 mm	(c)	The thickness of the solar glass used on the front side of the solar cell
	Back: EVA Back Foil	(a)	EVA back foil configurations based on the Guideline
	Cell number per panel: 72	(b)	Standard-based on the Guideline
Vehicle Integration	Panel Number: 3		
	Total PV Area: 4.8 m ²	(b)	
	PVCU Number 3		
	Mounting: on the rooftop		
Integration with Bosch Profiles			

(a) Guideline (Frischknecht et al. 2015) [7]; (b) STREET Internal Expert Judgement; (c) LCI on SHJ Cells (Louwen et al. 2016; Olson et al. 2013) [8,9].

For the solar cells in the VIPV, heterojunction technology (SHJ) was chosen due to the best trade-off between efficiency and costs. Thus, in the LCA, the cell heterojunction process was described by the following process steps taken from [8] and [10] and shown in Table 2. The metallization of the front side requires a double print of the standard amount of silver paste and sputtered aluminum closed back side. The LCI data on material and energy consumption were added for heterojunction cell processing, referring to [8–10].

Table 2. Process steps of heterojunction cell.

Process Step	Material	Description
Metallization front	Ag print	Screenprint
TCO	ITO	Sputtering of indium-tin-oxide
Emitter	a-Si: H (p)	ALD—atomic layer deposition
Passivation	a-Si:H (i)	Deposited by PECVD
BSF	a-Si:H (n)	Back surface field
Metallization back	Ag print	Screenprint

2.4. Input Parameters for the Energy Flow Model

The main factor for the estimation of PV electricity generation is the effective solar irradiance, which depends on the route and location, season, time, and module configuration and orientation. For the reference case of the LCA, the location for the operation was set in Cologne, Germany. The hourly global horizontal solar irradiance was defined by averaging hourly incident global horizontal radiation data extracted from the PVGIS database. The on-board generation of electricity was simulated based on degradation, system losses, and shadowing factor (see Table 3). A 19.7% module efficiency was assumed [9]. In line with IEA-PVPS methodology guidelines [7], degradation of 0.7% per year was applied. Operation time of the reference case was set to 8 years, based on data of LUVs in delivery services [11].

Table 3. Input parameters for the operation of the VIPV.

Parameter	Value	Unit
Capacity	930	Wp
Efficiency	19.7	%
Degradation	0.7	%
Operation lifetime	8	a
Location	Cologne (50.938, 6.954)	Lat/Lon
Database	PVGIS-CMSAF	/

According to the literature guidelines, efficiency for the VIPV system was estimated. Due to dynamic shading, an average 70% performance compared to residential PV was assumed [3]. Furthermore, generated energy cannot be used directly for traction of the vehicle and must be stored in the battery, where DC-Charging/discharging loss of 2% appears. Additional loss of 5% was considered due to the DC/DC converter. The loss of the MPP tracking additionally limits its efficiency in the model to 95% [3]. A performance loss of 9% due to temperature increase and low irradiance was assumed [5]. The overall average efficiency losses of the VIPV system is to be found in Table 4.

Table 4. VIPV system efficiency.

Loss Coefficient	Changes in Output (%)
MPPT loss	−5
Temperature/low irradiance	−9
DC/DC conversions	−5
DC charging/discharging loss	−2
Average shadowing factor	−30

2.5. Input Parameters of the Grid Charge

The grid mix in the location of the charge was analyzed regarding its carbon intensity. The emissions of the grid can vary massively depending on the different power plants. Fossil power plants dominate the power generation in Germany. Acknowledged studies usually consider annual average carbon footprints of the grid power plants caused by the life cycle (construction, fuel production, operation, etc.) [12]. Hourly average emissions of the German electricity mix vary depending on the day and night times. The German electricity mix was modelled using SMARD electricity generation data from 2017 and utilized for the projection of the future scenario [13].

The reference scenario follows the pathway of technological development as far as possible, according to the goals set by politics. The target of the electricity sector in Germany for 2030 is 180–186 Mio t. Until 2028, the annual electricity mix GWP is expected to decrease by 2% per year [1]. Table 5 gives an overview of the emissions of different electricity sources, found in [14].

Table 5. Emission factors of electricity sources.

Electricity Source	(g CO ₂ eq./kWh)	Reference
Biomass	272	[15]
Hydropower	3	
Pumped hydro	26	
Wind offshore	6	
Wind onshore	11	
Photovoltaics	67	[12]
Geothermal	192	
Lignite	1142	
Coal	815	
Natural gas	374	
Nuclear	32	[14]
German mix average	486	[12]

2.6. Reliability of the Data

The LCI in this study was based on extracting the data from reliable literature. The commercial LCA software GaBi Version 8.7.1.30 was used to model and calculate the LCI and impact assessment results. Essential materials, electricity mixes were calculated based on data represented by the Ecoinvent database unless otherwise noted. The International Energy Agency (IEA) developed guidelines to make the LCAs of PV systems more consistent and to enhance quality and reliability. Data on production is mainly based on these guidelines and LCIs of photovoltaics [7], additionally considering the heterojunction process of [9,10]. Some values for the Vehicle Integration Process and PVCU were adjusted after internal communication in STREET. The reason for adjustment was mainly a lack of access to the supply chain model data. The data used for this LCA varies in quality and reliability. To limit the resulting uncertainty, the differences of the data sources were analyzed and scored referring to the Quality Pedigree Matrix Flow Indicators determined by DIN 14044. Due to the above-mentioned conditions, the scores for each step were evaluated in Table 6. The highest score shows the lowest uncertainty and data scored with 5 shows the highest uncertainty.

Table 6. LCA data quality.

Process	Data Source	Quality	Comment	Flow Score
Feedstock, ingot, wafer production	(Frischknecht et al. 2015) Material flow: Ecoinvent database	Primary data, measured	High variability of process data, low uncertainty, verified data based on measurements with less than 6 years of difference	2
Wafer cleaning, texturing, PECVD of a-Si layers, TCO deposition, contacting, wiring	(Louwen et al. 2016; Louwen et al. 2012b; Olson et al. 2013) Material flow: Ecoinvent database	Primary data, measured, Ecoinvent processes updated based on updated data	Low variability of process data, low uncertainty, based on measurements with less than 6 years of difference	1
PVCU	Expert judgement—continental material flow: Ecoinvent database	Primary data, adjusted and verified by the STREET experts	Low variability of process data, higher uncertainty, verified by STREET Experts, less than 6 years of difference	2
Module assembly	(Frischknecht et al. 2015) Material flow: Ecoinvent database	Primary data, measured	Low variability, higher uncertainty, verified precise data based on measurements with less than 6 years of difference	2
Vehicle integration	Expert judgment: StreetScooter Material flow: Ecoinvent database	Estimated data based on metadata, verified by the STREET concept	High variability, high uncertainty, documented estimate, verified by STREET Experts, less than 6 years of difference	3
Operation	(PV-Powered Vehicle Strategy Committee 2019) Material flow: Ecoinvent database	Estimated data based on metadata, lacking measurements of PV output and maintenance	High uncertainty, high variability, documented estimate, verified by STREET Experts, less than 6 years of difference	3

3. Results

This section presents the results of the LCA study completed to the mid-point level.

3.1. Manufacturing Process of the VIPV

The results of the analysis of the manufacturing phase [$\text{kg CO}_2\text{eq}$] demonstrate the impact before the operation starts. The manufacturing process VIPV shows similar results to other PV systems. The most dominant contributor to this phase is the Solar-Grade Process. It is responsible for 444.30 kg CO_2

eq, a third of total emissions. The process of integration of the cells into the panel emits 235.24 kg CO₂ eq. The calculated total amount of emissions during the manufacturing process is 1143.12 kg CO₂ eq (see Figure 4).

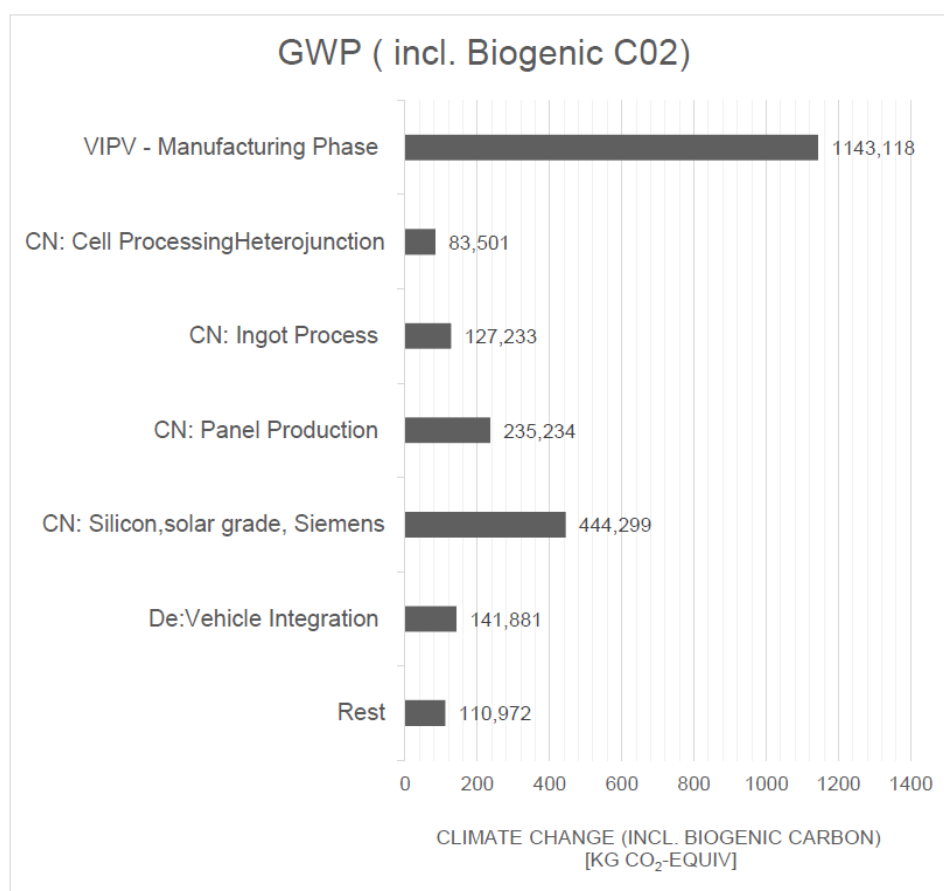


Figure 4. Results of the LCA, the manufacturing phase global warming potential (GWP) = 1143 [kg CO₂ eq].

3.2. Operation Phase of the VIPV

The on-board generation of electricity was simulated based on the assumptions on degradation, system losses, and shadowing factor, as previously described in Section 2.4. While driving the EV, the batteries will discharge and will recharge again using the on-board PV modules. The degree of VIPV's impact was expected to vary with the usage patterns: different daily driving distances have different depths of discharge corresponding to daily driving durations. In this study, all incoming irradiance during the day is used, assuming energy is being collected and the battery is being charged, even if not driving. The results of the energy flow model are shown in Table 7.

Table 7. Results of the energy flow model.

Parameter	Value	Unit
Average yield in urban area	936	(kWh/kWp)
Average annual VIPV electricity production on board	479	(kWh/year)
Total production VIPV	3738	(kWh)

For the reference scenario of 8 years operation and a shadowing factor of 30%, the VIPV contribution is 3738.116 kWh. Prolonged operation of 12 years generates 5526.702 kWh in total.

3.3. Comparison to the Emissions of the Grid Charge

For the same amount of energy, if the grid would be used, 1630 kg CO₂-eq for 8 years and 2267 kgCO₂-eq for 12 years were calculated. The losses appearing due to grid distribution were not calculated, because the emission factor is already based on an energy consumption perspective.

Main findings of the comparison with grid electricity show: VIPV can improve the carbon footprint for the reference case of an average shadowing factor of 30% and 8 years of operation time. For the functional unit of 1 kWh of on-board generated PV electricity, the emission factor of 0.357 kgCO₂-eq/kWh is calculated for the reference case. In comparison, the average grid emissions for the operation time are expected to be 0.435 kgCO₂-eq/kWh.

Considering the data quality of the LCA, reduction of emissions of the functional unit for the reference case compared to the grid is about 18%. The holistic view of the results for the reference case shows 3738 kWh VIPV contribution. For the functional unit of 1 kWh of on-board generated PV electricity, the emission factor of 0.357 kgCO₂eq/kWh is calculated. In comparison, the average grid emissions for the operation time are expected to be 0.435 kgCO₂eq/kWh. Compared to the estimated grid average, about 18% less emissions per kWh are caused by VIPV. Projected contribution of VIPV was replaced by grid charging to find out in which operation year VIPV have fewer emissions than the grid and thus calculate the “ecological break-even point”. In the previously described reference case, this point is achieved in the year 2022. That means that after 6.5 years of operation, the ecological impact of VIPV equals the impact of the grid charge. However, an increasing shadowing factor of mobile application causes a significant growth of emissions per kWh.

3.4. Sensitivity Analysis

The results of the study are wide-ranging. The variations mainly arise from system operating assumptions (e.g., solar irradiation, system lifetime, shadowing factors) and technology improvements (e.g., electricity consumption for manufacturing processes). In this section some adjustments of the reference case (8 years of operation, 0.7% degradation, and 30% shadowing factor) are considered.

PV-generated power is an essential variable for the reduction in emissions. By increasing the shadowing factor, emissions per kWh grow significantly. An emission factor of 0.357 kgCO₂-eq/kWh is calculated for the reference case. The increased shadowing factor of 40% results in 0.435 kgCO₂-eq/kWh, which equals the average emissions of the future grid electricity. As shown in Figure 5, the ecological benefit over the grid charge disappears completely when the shadowing factor reaches 40%.

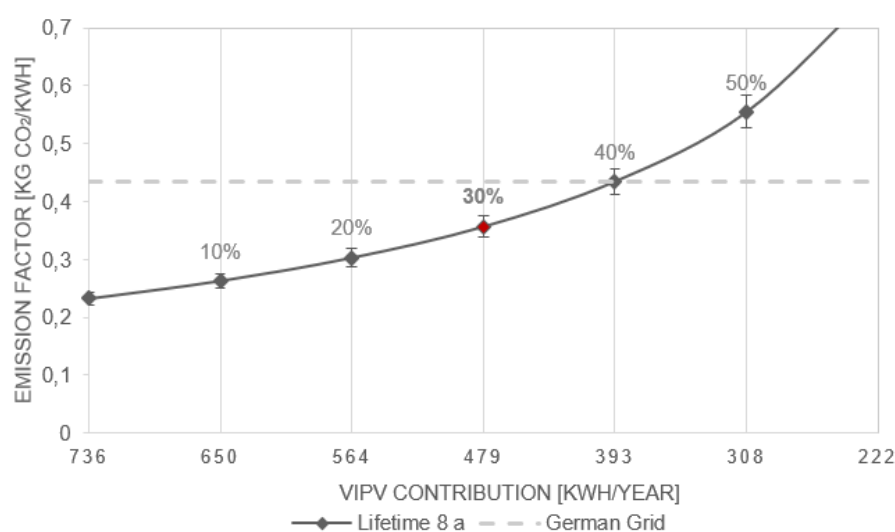


Figure 5. Emissions depending on the shadowing factor.

Sensitivities show that if the VIPV is used for a prolonged life of 12 years, the emission factor of the produced electricity decreases to 0.221 kgCO₂-eq/kWh. A reduction of 38% (0.136 kgCO₂-eq/kWh) compared to the reference case of 8 years is noted. The average grid mix emissions of prolonged use decrease to 0.409 kgCO₂-eq/kWh. Comparable results can be achieved with a shadow factor of 55% or an average annual VIPV generation of about 260 kWh/a. Lifetime extension of the vehicle operation will automatically result in a reduction of the emissions per produced kWh of the VIPV. Figure 6 demonstrates the potential of the longer operation phase for different shadowing factors.

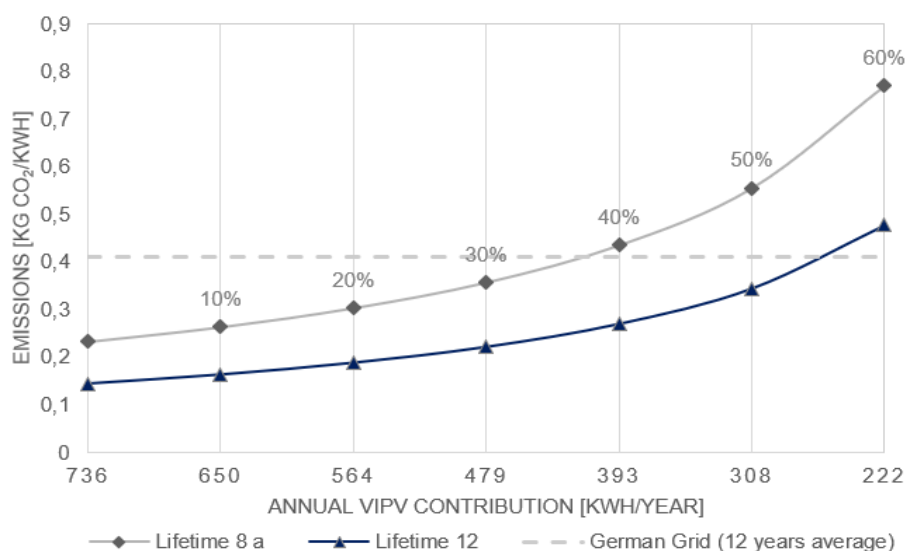


Figure 6. Emissions of “prolonged use” scenario.

Based on findings of the sensitivity analyses, the highest potential for emission reduction can be confirmed for a “green” electricity scenario, where renewable electricity is used for the manufacturing process. The emission factor of 0.831 kgCO₂/kWh for the electricity mix of China used for the simulation of the reference case is based on the GaBi Education Database from 2017. With the increasing share of renewable energy in the electricity mix, lower GWP impact will arise from the production phase of the VIPV. Using green electricity has the potential to be almost carbon-free, as is the case for today’s hydropower. For “green” electricity, assumptions of hydro plants with average emissions of 0.003 kgCO₂-eq/kWh were used to cover the energy need of the manufacturing phase in China [15]. As illustrated in Figure 7, the emissions decrease from 0.357 to 0.230 kgCO₂-eq/kWh for the shadowing factor of 30%.

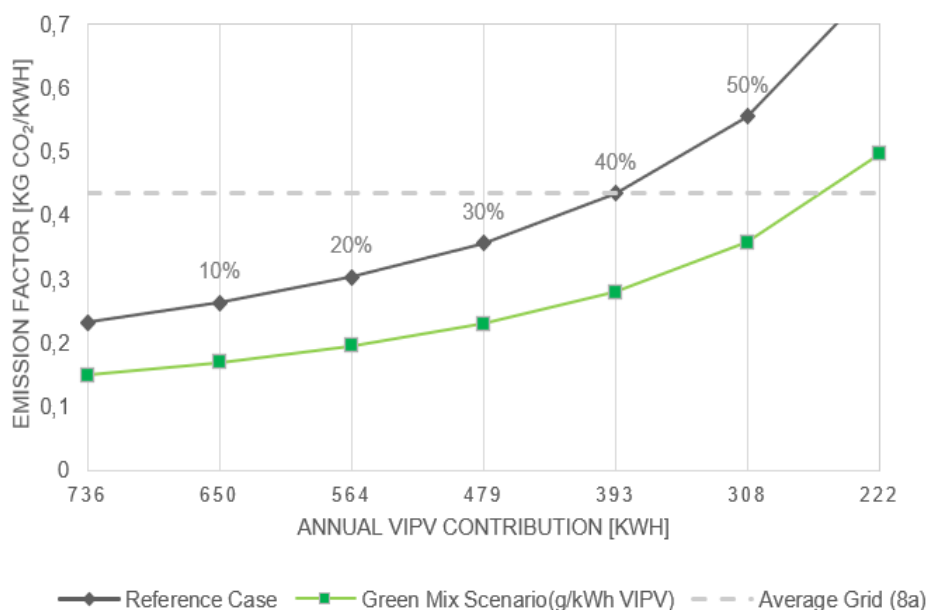


Figure 7. Emissions of “green manufacturing” scenario.

4. Discussion and Conclusions

The study reports the unique observation that placing a PV system on-board of an existing StreetScooter can improve the carbon footprint of the generated electricity for the reference case of an average shadowing factor of 30% and 8 years of operation time. The ecological benefits of PV-powered light utility vehicles are confirmed for the reference case of the StreetScooter. Yet, the results of the LCA show that viability is heavily dependent on the vehicle’s deployment region and usage scenario. Main findings of the comparison to the grid electricity show: VIPV can improve the carbon footprint for the reference case of an average shadowing factor of 30% and 8 years of operation time. For the functional unit of 1 kWh of on-board generated PV electricity, the emission factor of 0.357 kgCO₂-eq/kWh is calculated. In comparison, the average grid emissions for the operation time are expected to be 0.435 kgCO₂-eq/kWh. Considering the data quality of the LCA, reduction of emissions of the functional unit for the reference case compared to the grid is about 18%. By increasing the shadowing factor, emissions per kWh grow significantly. The ecological benefit to the grid charge disappears completely when the shadowing factor reaches 40%. However, if the operation time is prolonged to 12 years, the shadowing factor can reach 55%, having similar emissions to grid charge. For the reference case with 30% shadowing, a reduction of 38% compared to 8 years in use can be noted. For this case, 0.221 kgCO₂-eq/kWh is estimated for the functional unit.

One of the key challenges of this work was finding an appropriate vehicle usage model to reproduce the ratio of using solar power and performance assessment of Maximum Power Point Tracker (MPPT) algorithms for VIPV. Tests with radiation sensors investigating shading and reflection conditions are suggested. Numeric simulation of VIPV output test drives with irradiance profiles of routes should include different vehicle usage times, effects of panel position and movement. Additionally, it is necessary to address the electrical and technical issues.

For the recycling process, no established and reliable routes were found. As to the knowledge of the author, no study provides details on the LCI with the input and output of every process stage. However, if material depletion is considered, recycling is crucial, and further research should include recyclability options. Since second use is an important issue, the mounting structure, removable, and lightweight, must become a priority for research. Furthermore, a scenario of VIPV connection to the public grid while parking during weekends, in which the surplus of unused electricity can be fed into the grid, seems to be realistic. Vehicle2Grid (V2G) concepts can be very profitable, but first, the dependence on the state of charge (SOC) of the battery including an ageing model of the battery with

charging and discharging losses should be analyzed. Enhanced communication and cooperation between automotive companies and PV players can contribute to the positive image of vehicle integrated photovoltaic systems in order to achieve the goal to change the image of VIPV. Likewise, international methods for evaluating the reduction of emissions of PV-powered vehicles can help to communicate the created value for the different driving and charging behaviors. To contribute to the growth of the VIPV market, governments willing to achieve emission goals must support the standardization of the technology. To solve this problem, international methods of evaluating added value on the reduction of grid power and ecological benefits are required.

Author Contributions: Conceptualization O.K., K.D.; methodology O.K., J.M.; software, validation, investigation, resources, data curation and writing—original draft preparation O.K.; writing—review and editing A.R., J.M., K.D.; visualization, O.K.; supervision J.M., A.R., project administration K.D.; All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Federal Ministry for Economic Affairs and Energy in the framework of the STREET project (grant: DB001618).

Acknowledgments: This work is based on the Master's thesis by Olga Kanz at the Hochschule Köln 2019. The authors appreciate the support of the research group of IEA Photovoltaic Power System Programme Task 17, which focuses on possible contributions of photovoltaic technologies to transport and support from Toshio Hirota and Keichi Komoto. Costs for publishing are covered by Forschungszentrum Jülich GmbH.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. European Environment Agency (EEA). Progress of EU Transport Sector Towards Its Environment and Climate Objectives, 2018. Available online: <https://www.eea.europa.eu/themes/transport/term/term-briefing-2018> (accessed on 30 September 2020).
2. Helmers, E.; Dietz, J.; Hartard, S. Electric car life cycle assessment based on real-world mileage and the electric conversion scenario. *Int. J. Life Cycle Assess.* **2015**, *22*, 15–30.
3. New Energy and Industrial Technology Development Organization. NEDO, PV-Powered Vehicle Strategy Committee, 2018. Available online: <https://www.nedo.go.jp/content/100885778.pdf> (accessed on 30 September 2020).
4. Rizzo G.. Automotive application of solar energy. In Proceedings of the 6th IFAC Symposium Advances in Automotive Control, Munich, Germany, 12–14 July 2010.
5. Araki, K.; Ji, L.; Kelly, G.; Yamaguchi, M. To Do List for Research and Development and International Standardization to Achieve the Goal of Running a Majority of Electric Vehicles on Solar Energy. *Coatings* **2018**, *8*, 251, doi:10.3390/coatings8070251.
6. Environmental Management—Life Cycle Assessment—Requirements and Guidelines (ISO 14044:2006 + Amd 1:2017); German Version EN ISO 14044:2006, 2006.
7. Frischknecht, R.; Itten, R.; Sinha, P.; de Wild-Scholten, M.; Zhang, J. *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems, IEA PVPS Task 12, Subtask 2.0*; Life Cycle Assessment Report IEA-PVPS 12; International Energy Agency: Paris, France, 2015.
8. Louwen, A.; Van Sark, W.; Schropp, R.E.I.; Faaij, A. A cost roadmap for silicon heterojunction solar cells. *Sol. Energy Mater. Sol. Cells* **2016**, *147*, 295–314.
9. Olson, C.; de Wild-Scholten, M.; Scherff, M. Life Cycle Assessment of Hetero-junction Solar Cells. In Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany, 5–6 September 2011.
10. Louwen, A.; van Sark, W.; Turkenburg, W.C.; Schropp, R.; Faaij, A.C. R&D Integrated Life Cycle Assessment: A Case Study on the R&D of Silicon Heterojunction (SHJ) Solar Cell Based PV Systems. In Proceedings of the 27th European Photovoltaic Solar Energy Conference and Exhibition, Frankfurt, Germany, 23–27 September 2012; pp. 4673–4678.
11. Hacker, F.; Waldenfels, R.; Moschall, M. Wirtschaftlichkeit von Elektromobilität in Gewerblichen Anwendungen. Betrachtung von Gesamtnutzungskosten, Ökonomischen Potenzialen und Möglicher

- CO₂EQ—Minderung im Auftrag der Begleitforschung zum BMWi Förderschwerpunkt IKT für Elektromobilität, 2015.
12. Icha, P. Entwicklung der Spezifischen Kohlendioxid-Emissionen des Deutschen Strommix in den Jahren 1990–2018, 2019. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-04-10_cc_10-2019_strommix_2019.pdf (accessed on 30 September 2020).
 13. Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen. SMARD, 2020. Available online: <https://www.smard.de/home> (accessed on 22 June 2020).
 14. May, J.F.; Kanz, O.; Schürheck, P.; Fuge, N.; Waffenschmidt, E. Influence of usage patterns on ecoefficiency of battery storage systems for electromobility and home storage. In Proceedings of the 3rd Product Lifetimes and the Environment Conference, Berlin, Germany, 18–20 September 2019.
 15. Memmler, M.; Lauf, T.; Schneider, S.; Dessau-Roßlau, U. Emissionsbilanz Erneuerbarer Energieträger — Bestimmung der Vermiedenen Emissionen im Jahr 2017, 2018. Available online: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-10-22_climate-change_23-2018_emissionsbilanz_erneuerbarer_energien_2017_fin.pdf (accessed on 30 September 2020)



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).