



# Environmental Impacts of Photovoltaic Powered Mobility

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**Environmental Impacts of Vehicle Integrated Photovoltaics:**  
a Life Cycle Assessment of a Solar Electric Vehicle

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## Abstract

Solar electric vehicles (SEVs) with integrated photovoltaic (PV) cells have the potential to decrease the related greenhouse gas emissions of regular BEV charging from the electricity grid. However, the environmental impacts and potential areas of improvement of such SEVs is yet under-explored. The aim of this study is to assess the environmental impacts of the vehicle integrated photovoltaics (VIPV) and to assess whether an SEV could act as a sustainable substitute for battery electric vehicles (BEVs) without VIPV. A life cycle assessment is performed to assess the environmental impacts from the cradle-to-grave life cycle, where an SEV is compared to a BEV without VIPV. Several environmental impact categories have been assessed: climate change (CC), acidification (AC), energy resources (ER), fossil depletion (FD) and metal depletion (MD). A scenario LCA and sensitivity analysis have been performed to assess the influence of changing parameters on the CC impacts. The sensitivity analysis included different modelling decisions on vehicle efficiency, global horizontal irradiation and driving behavior. With a functional unit of 200,000 vehicle kilometers (vkm) the SEV resulted in lower CC impacts (compared to a BEV). Other impact categories show lower results for the SEV compared to the BEV after a use-phase of 200,000 vkm. The total functional unit of 200,000 vkm resulted in 3,300 kg CO<sub>2</sub>-eq less CC impacts for the SEV compared to the BEV without VIPV with similar vehicle characteristics. However, environmental impacts related to VIPV production were higher than the production of a regular vehicle exterior which means that the production phase of an SEV causes more impacts than the production of a BEV. In the reference case LCA, results showed that the break-even point of CC impacts between the SEV and BEV occurs at a distance driven of 79,000 vkm (6.1 years of operation in the Netherlands). Sensitivity analyses showed that the CC impacts are influenced by factors such as vehicle efficiency, global horizontal irradiation (GHI) and driving behavior. This study concludes that increasing vehicle efficiency seems to effectively decrease CC impacts similar to the effect that VIPV can have on a vehicle and improving vehicle efficiency can potentially even contribute more to use-phase CC impact savings than substituting a regular exterior by VIPV. Second, the GHI influences CC impacts of the SEV as the ratio of VIPV-electricity to grid-electricity depends on the amount of solar energy that is converted into electricity by the VIPV. Third, a driving behavior that enables the SEV to maximise its share of electricity powered by the VIPV showed the least CC impacts. Importantly, the lower CC impacts from SEVs compared to BEVs does not imply that SEVs are the most sustainable mode of transportation whereas there exist other less carbon-intensive alternatives (e.g. bikes and public transportation).

## Keywords

*Solar electric vehicle, vehicle integrated photovoltaics, battery electric vehicle, environmental impacts, life cycle assessment, mobility, transition.*

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## Abbreviations

**AB** Activity Browser.

**AC** Acidification.

**BEV** Battery Electric Vehicle.

**CC** Climate Change.

**ER** Energy Resources.

**EV** Electric Vehicle.

**FD** Fossil Depletion.

**GHG** GreenHouse Gas.

**GHI** Global Horizontal Irradiation.

**IAM** Integrated Assessment Model.

**ICEV** Internal Combustion Engine Vehicle.

**IE** Industrial Ecology.

**LCA** Life Cycle Assessment.

**LCI** Life Cycle Inventory.

**Li-ion** Lithium-ion.

**MD** Metal Depletion.

**NMC** Nickel-Manganese-Cobalt.

**PV** Photovoltaic.

**RCP** Representative Concentration Pathway.

**SDGs** Sustainable Development Goals.

**SEV** Solar Electric Vehicle.

**SSP** Shared Socio-economic Pathway.

**V2G** Vehicle-to-Grid.

**VIPV** Vehicle Integrated Photovoltaics.

**WTW** Well-To-Wheel.

# 1 Introduction

## 1.1 Background

As pandemic restrictions were relaxed in 2021 and passenger and freight movements started to pick up again after their extraordinary decrease in 2020, worldwide CO<sub>2</sub> emissions from the transportation sector rose tremendously, increasing roughly by 8% from 7.1 Gt CO<sub>2</sub> up to 7.7 Gt (IEA, 2022) (Figure 1). Following the Net Zero Scenario requires a 20% reduction in emissions from the transport sector to decrease to 6 Gt by the end of 2030, even while increases in transportation demand are expected. The global development of transport is increasingly dependent on the performance of global supply chains and energy systems, which currently contributes to these rising global warming issues. The release of the IPCC report (IPCC, 2022) has stressed the urgent need for a fast transition towards a zero-emission transport sector to reach CC goals. An energy transition towards renewable energy sources is required to create a pathway towards zero-emission transport. Despite global efforts by governments to reduce global warming impacts, the CO<sub>2</sub> emissions have been increasing by 60% since the agreement of the United Nations Framework Convention on Climate Change in 1992 (UNFCCC, 1992). Alongside this agreement, there are others such as the Paris Climate Agreement and Sustainable Development Goals (SDGs) which formulated sustainability goals to halt global warming.

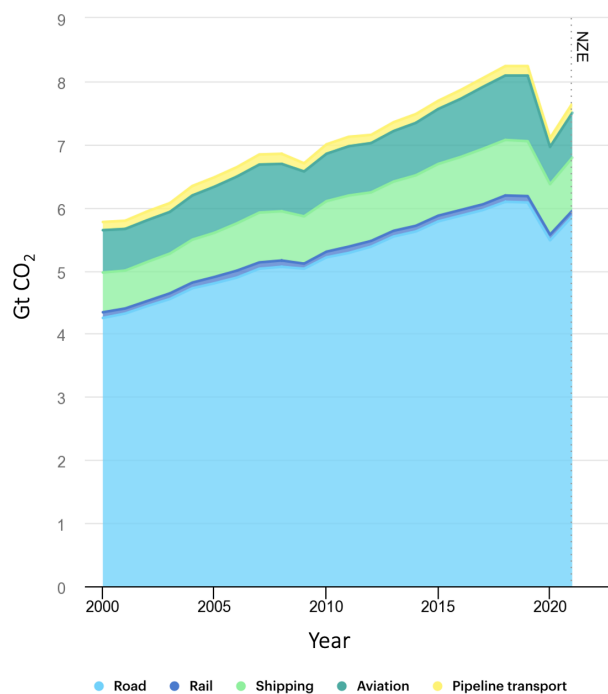


Figure 1: Transport emissions projected over time (IEA, 2022).

The attention of sustainable transport goals has increased by acts such as the European Green Deal (European Commission, 2019). To reach the goal of net zero mobility, the use of Internal Combustion Engine Vehicles (ICEVs) does not longer fit into a sustainable pathway for the future. Achieving the required drop in transport related emissions has emerged attractiveness of alternatives to ICEVs, which gained serious attention to the electrification of the vehicle fleet. An ICE burns fuel directly which emits GreenHouse Gas (GHG) to the atmosphere, while an Electric Vehicle (EV) has an integrated electric motor that does not emit GHGs at the tailpipe. In the last two decades, EVs have been going through a strong developmental phase, as the zero-emission motor of EVs could provide a path towards net-zero emissions in the transportation sector. Owing to the transition,



(a) PV-powered charging stations. Source: Automotiveworld (2022)



(b) Hyundai Ioniq 5 with VIPV. Source: Hyundai (2022)

Figure 2: Indirect (a) and direct (b) use of PV-panels for EV charging.

vehicle emission standards have been adopted by the European Commission to reduce 90% of GHG emissions in transport by 2050 (European Commission, 2019). Therefore, by 2030 the aim of the European Commission is to have at least 30 million zero-emission cars and 80.000 zero-emission lorries in operation.

Although, Battery Electric Vehicles (BEVs) do have the environmental benefit of no tailpipe emissions compared to ICEVs, a BEV relies on charging its built-in battery by the local electricity grid. As long as the electricity grid is powered by fossil-fuel sources, the charging of BEVs still emits CO<sub>2</sub>. In 2020, the global electricity grid was generated for 61% by fossil fuels. In the Netherlands specifically, the share of electricity sources in 2021 was 63% fossil fuels, 3% nuclear and 34% renewables (Ritchie & Roser, 2020). Which means that BEVs charged by the local grid are generally not yet contributing to zero-emission transport.

One of the solutions to tackle this problem would be to increase the share of renewable energy sources to provide electricity for BEV charging. The use of Photovoltaic (PV) systems could increase the direct use of renewable energy to power the battery of the BEV, which decreases the dependency on charging from the local electricity grid. There are two ways to integrate these PV systems into the BEV charging system: indirectly via PV-powered charging stations (Figure 2a), or directly via integrated PV-cells on the vehicle's exterior: referred as Vehicle Integrated Photovoltaics (VIPV) (Figure 2b). The BEV-PV charging systems (both directly and indirectly) have several advantages: 1) a reduction of BEV charging by the electricity grid due to the energy generation by the PV-cells; 2) less overloaded local electricity grids which increases the grid flexibility (Sierra Roiguez et al., 2020); 3) a higher energy efficiency in direct PV cell to EV battery connection compared to energy drawn from the grid; and, 4) the feasibility of discharging the PV-generated electricity to the grid: Vehicle-to-Grid (V2G) (Khan et al., 2018).

#### *Vehicle integrated photovoltaics*

A VIPV system provides energy to the vehicle which directly converts solar energy to electricity that charges the battery of the BEV. A study has estimated that a BEV with VIPV can have an extensive annual driving range without additional charging under extremely high annual irradiation conditions or PV-cell efficiency of roughly 30% or more (figure 2) (Sierra Roiguez et al., 2020), however, this seemed highly dependent on vehicle parameters such as energy efficiency. There are several other factors which play an important role in the added value of VIPV among which the amount of power generated by the PV-cells, the solar array size and the maximum solar yield.

First, the power generation of the PV-cells is dependent on various factors among which the PV-cell efficiency, curvature of the vehicle's surface, solar irradiation, geographic location, weather conditions, ambient temperature, wind speed, and dust deposition (Hachicha et al., 2019). Second, the array size of the PV-surface defines the quantity of solar energy that can be generated at one point in time. Third, the maximum solar yield of the VIPV determines the peak electricity conversion yield of the system. These three factors together define the

amount of electricity which can be generated to charge the BEV. The higher the amount of electricity generated by the VIPV, the less electricity will be required to charge from the grid.

A drawback of the addition of a PV-system to a vehicle is that it increases the weight of the car as it requires heavier materials (solar panels and glass) and a solar conversion system (including a low voltage battery system) than a regular vehicle exterior. Integrating the PV system on the BEV's exterior thus has mainly three consequences: 1) a slight increase in vehicle weight due to the PV materials and solar conversion system, 2) a decrease in energy demand of the electricity grid due to direct energy generation by the VIPV system, and 3) an increase in material demand and manufacturing energy due to VIPV production.

## 1.2 Knowledge gaps

In scientific literature there exist many studies on the deployment on solar-assisted BEV charging stations, however, previous studies mainly focus on the application of PV-systems to BEV charging stations and the field of the environmental performance of VIPV seems rather unexplored. A summary of the research that has been previously done on BEV-PV systems can be found below.

The role of existing fuel stations infrastructure in deploying solar charging systems has been explored by Alghoul et al. (2018) and Birnie (2016). The performance of PV microgrids has been assessed (N et al., 2021; Novoa & Brouwer, 2018). Khan et al. (2018) and Bhatti et al. (2016) performed a review assessment of solar charging systems for BEVs. Sierra Roiguez et al. (2020) explored how well PV systems might contribute to charging of BEVs in four different countries. In addition, some studies have been done on PV-integrated vehicles for material optimisation (Ghose et al., 2019), analysis of energy capture (Birnie, 2009) and reliability and availability modeling (Talukdar et al., 2021). With the use of Life Cycle Assessment (LCA) the global warming impacts have been previously assessed for regular BEVs already (BMW Group, 2020; Bolin, 2020; Nordelöf et al., 2014) and for specific BEV components such as the battery (Nordelöf, 2018). One study has been done to assess the environmental impacts of integrated PV modules in light utility electric vehicles (Kanz et al., 2020). Another LCA study has been performed which used literature data to assess the environmental impacts of integrated PV-panels in vehicles (Abdelhamid, 2014). Results of these two studies have shown that implementing PV-panels in vehicles show a significant decrease in CC impacts in the operation phase of the BEV.

As of the author's knowledge, there are no other LCA studies performed on PV integration in vehicles. Therefore, it is beneficial to conduct an LCA study in this research topic as the VIPV technology is an emerging technology that is not researched thoroughly. An LCA is a suitable research technique to assess the environmental impacts of a product system as it quantifies all the relevant emissions and resources consumed, the related environmental impacts, and resource depletion issues that are related with any goods or services (European Commission, 2010). The results of an LCA can assist in identifying opportunities to increase the environmental performance of a product system (ISO, 2006). The previous VIPV LCA study has focused on light utility vehicles (Kanz et al., 2020). Therefore, to close the research gap this study focuses on medium weight passenger electric vehicles and includes an assessment of several impact categories. In addition, it provides a direct comparison between a Solar Electric Vehicle (SEV) with integrated PV-system and a BEV with a regular surface.

Expanding the scientific knowledge on environmental performances of SEVs is required to enable fair comparisons between SEVs and BEVs without VIPV. In addition, it can help to make the right choices to further minimise environmental impacts of SEVs. As the main reason to develop SEVs in the first place is to potentially decrease global warming impacts related to BEVs, assessing its actual environmental impacts will determine whether SEVs can act as a sustainable substitute for BEVs without VIPV.

A review study of previously done LCA studies on EVs has observed the following (Nordelöf et al., 2014): 1) a critical note that was mentioned was the frequent absence of a comprehensive goal formulation according

to the ISO standards (ISO, 2006). Reviewed studies lacked a proper time scope and focused on current electric vehicle technology, while in fact BEV innovations are developing in a high pace. 2) Focus was often laid on global warming impact categories, which provokes conclusions that vehicles are environmentally friendly, while in fact they can perform worse in other impact categories such as resource depletion. To deal with these two aspects, this study has incorporated this feedback by: 1) formulating a clear goal and scope, and 2) assessing multiple environmental impact categories to not overlook other environmental issues that can influence the environmental impacts of SEVs.

With this study it is aimed to contribute to existing research literature and close knowledge gaps by providing the following:

- An overview of the environmental impacts of an SEV in multiple impact categories.
- An assessment of how factors such as vehicle efficiency, solar irradiation and driving behavior influence the environmental impacts of sev.

### 1.3 Problem statement

Integrating a PV-system in a BEV might reduce the use of fossil-fuel based grid electricity, however, the production of such a VIPV system does require additional materials and manufacturing energy compared to a regular vehicle exterior (without VIPV). Therefore, it is important to assess the environmental impacts of the increased material and energy use related to VIPV production. The question is whether the integration of a VIPV system in an BEV can contribute to mitigate CC effects. In order to have an environmental benefit compared to BEVs with a regular exterior, the PV panels must be able to generate a significant amount of electricity to outweigh the environmental impacts that are caused by the production of the VIPV system.

### 1.4 Research objective and research question

The research objective of this study is to assess the environmental impact of an SEV. With that it is aimed to assess whether an SEV has creates less environmental impacts than BEVs with regular exterior. However, this study does not capture the complete environmental performance as it does not assess economic impacts or social impacts. To fulfill the stated objective, the main research question (RQ) to be answered by this study is formulated as:

1. ***“What are the potential environmental impacts of an SEV with VIPV system compared to a BEV with a regular exterior?”***

To provide an in-depth answer on the stated research question an LCA study performed that tried to answer the following sub-research questions:

2. "What are the potential environmental impacts of an SEV with VIPV system that is charged with an average EU electricity mix in 2020?"
3. "What are the environmental impacts of a BEV without VIPV system that is charged with an average EU electricity mix in 2020?"
4. "What is the effect of different CC mitigation scenarios on the CC impacts of an SEV?"
5. "What is the effect of vehicle efficiency, Global Horizontal Irradiation (GHI) and driving behavior on the CC impacts of an SEV?"

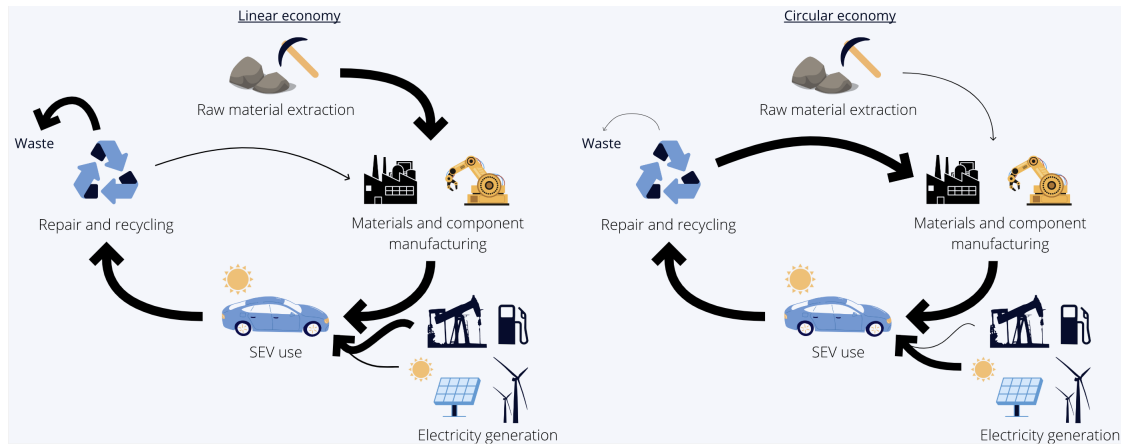


Figure 3: Representation of the SEV life cycle in a linear economy principle (left) and more circular economy principle (right). The arrow thickness indicates the quantity of material and product flows.

## 1.5 Industrial Ecology relevance

As this research is part of the fulfillment of the MSc degree in Industrial Ecology (IE), the study aims to add value to this scientific area. IE is "a field of study focused on the stages of the production processes of goods and services from a point of view of nature, trying to mimic a natural system by conserving and reusing resources" (Chertow et al., 2008).

By researching the potential environmental impacts of VIPV the potential value of this innovation to mitigate CC can be assessed. To possibly claim environmental benefits by integrating photovoltaic systems in BEVs it must be scientifically researched whether the impacts from manufacturing and production of the VIPV system are not decreasing the overall environmental performance of the SEV. To potentially minimise environmental impacts from SEVs, it should be assured to aim for a circular economy principle that conserves and reuses resources (Figure 3). Striving for circularity from the start of the research and design of the VIPV technology could minimise environmental impacts already from an early stage of development.

## 1.6 Reading guide

This report continues with an elaboration on the LCA methodology and framework that was used in this study (Section 2). That section explains the four phases that are covered in this LCA study: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation. Continued with Section 3 that covers the second phase (life cycle inventory) of the LCA framework including the data that was used to perform this study. Then, the third phase (life cycle impact assessment) is done in Section 4 where the reference case LCA, scenario LCA and sensitivity analyses on GHI, vehicle efficiency and driving behavior have been performed. The interpretations of results and limitations of the study are written in Section 5. Section 6 gives answers on the stated research questions, draws conclusions and gives recommendations for future research.

## 2 Methods

### 2.1 Life Cycle Assessment

To provide a scientifically relevant LCA, the International Organisation for Standardisation (ISO) 14044 framework was used as a guideline for the life cycle study (ISO 14044, 2006). This framework is developed to assess environmental impacts with the proper use of LCA research techniques. The modelling of the LCA has been done in the open source software Activity Browser (AB) which was developed by the Institute of Environmental Sciences of Leiden University (Steubing et al., 2020). The AB is a Python based open source LCA framework, which provides a graphical user interface that builds upon the LCA software Brightway 2 (Mutel, 2017). The software was used to implement LCI data and perform life cycle impact assessments. The study followed the general LCA framework which consists of 1) goal and scope formulation, 2) Life Cycle Inventory (LCI), 3) life cycle impact assessment and 4) interpretation (Figure 4). Starting with the goal and scope formulation.

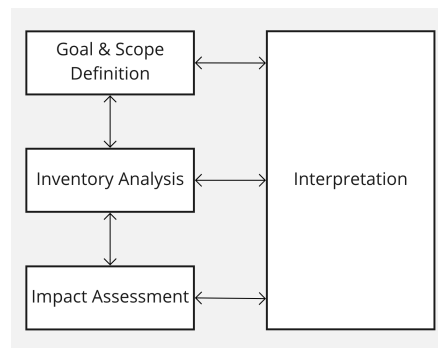


Figure 4: General framework of the scientific LCA method.

### 2.2 Goal and scope

In the first phase of an LCA, the goal and the scope of the study are defined. The goal of this study was to assess the environmental impacts of an SEV with VIPV and to compare these with the impacts of a BEV with a regular exterior. An additional goal of this study includes to assess whether an SEV could potentially act as a sustainable substitute for BEVs without VIPV.

To enable a comparison of the environmental impacts, the two different vehicle systems were analysed: the SEV (including a VIPV exterior) and the BEV (including a regular vehicle exterior) (Figure 5). To enable a direct comparison between a vehicle with VIPV and a vehicle without VIPV, it is chosen to model all components that are not related to the VIPV system with identical data. Thus, the glider, electric motor and battery are modelled identically for the SEV and BEV. By doing so, the model of the BEV without VIPV acts as a benchmark vehicle that enables direct comparison to a vehicle with VIPV: the SEV. It is chosen to assess the entire vehicles (not solely the VIPV system versus a regular vehicle exterior) in order to include differences in the use-phase of the two vehicles. The researched vehicles and their material differences are shown in Figure 5.

In the scope of an LCA study, the function of the studied product system is formulated in order to define the functional unit. The function that is provided by the studied vehicles is the distance that is driven. According to this function, a functional unit was chosen based on the amount of kilometers driven by the vehicle. The functional unit was defined as follows: *200,000 vehicle kilometers (vkm)*.

## 2.3 Study framework

This LCA study was conducted as follows:

- A reference case LCA which assesses the impacts of driving 200,000 vkm with an SEV compared to a BEV which includes base assumptions. Aimed to answer the first two sub-questions: "What are the potential environmental impacts of an SEV with VIPV system that is charged with an average EU electricity mix in 2020?" and "What are the environmental impacts of a BEV without VIPV system that is charged with an average EU electricity mix in 2020?".
- A scenario LCA that models changes in parameters representing several CC mitigation scenarios that differ in ambitiousness. This was aimed to answer the sub-question: "What is the effect of different CC mitigation scenarios on the CC impacts of an SEV?".
- Three sensitivity analyses that assess different modelling parameters in vehicle efficiency, solar irradiation and driving behavior. This was aimed to answer the sub-question: "What is the effect of vehicle efficiency, GHI and driving behavior on the CC impacts of an SEV?".

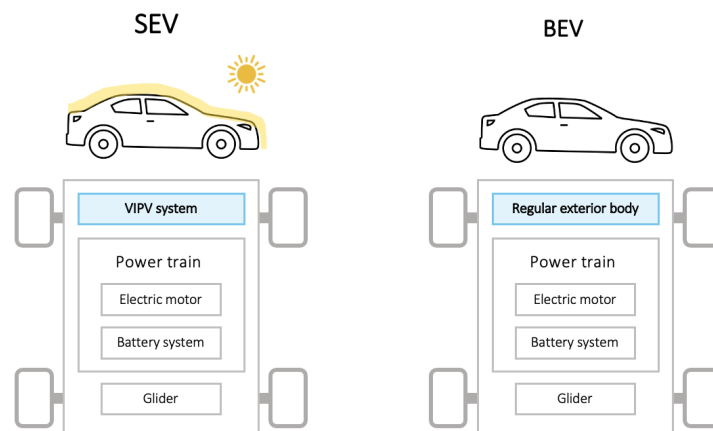


Figure 5: The two studied vehicle systems. In blue the different exterior systems that differentiate the vehicles.

### 2.3.1 Assumptions

To model the reference case of this LCA study, several base assumptions were made. A 'cradle-to-grave' approach was used, which means that all environmental impacts related to the following life cycle phases have been included: material extraction, vehicle manufacturing, electricity generation and conversion, use, and end-of-life.

- *Lifetime assumptions*

The functional unit of 200,000 vkm was chosen to represent the full lifetime of the SEV and BEV. The common lifetime assumptions from previous LCA studies and reports on EVs vary between 150,000 km, 200,000 km and 250,000 km (BMW Group, 2020; Hawkins et al., 2012; Hawkins et al., 2013; Polestar, 2020). To date, electric vehicle technologies have shown longer lifetimes than expected due to battery innovation, which is why modern cars are estimated to last at least 250,000 km (Auke Hoekstra & Steinbuch, 2020). For the reference case of this study, a mid-way assumption of 200,000 vkm lifetime is chosen.

- *Temporal assumptions*

For the reference case this study assumes that the operation phase of the vehicles takes place in 2021. The carbon intensity of the electricity grid that is used for vehicle charging is derived from the ecoinvent

3.8 dataset representing the EU electricity-grid as it is in 2021. Some primary data assumptions were made that represent the technology at a more mature state, which the technology is expected to be in late 2022.

- *Technology assumptions*

Several technology assumptions have been made for the reference case LCA (Table 1). First, the SEV is considered as a highly efficient vehicle (9,8 kWh/100 km) which is based on data from the vehicle manufacturer. Second, an assumption is made on the percentage of effective use of PV-cells. During this study, in the manufacturing process of the VIPV systems PV-cells were being cut to smaller shapes. A share of these cells is remains unused or is wasted. For the purpose of this LCA, the use of PV-cells is considered to be a 100% without any cells ending up into waste. This modelling choice is made to provide an expected - and optimistic - estimation of the future state of the VIPV production process. Third, the efficiency of the PV-cells was considered to be 23%, meaning that the amount of solar energy coming into the PV-cell is converted for 23% to electricity. Another assumption was made on the effect of weight difference between the VIPV system and the regular exterior system. As the VIPV system requires a solar conversion system and a small extra battery that weigh approximately 37.5 kg more than the regular exterior. This difference weight realistically decreases the vehicle efficiency of the SEV compared to the BEV. However, the weight difference is considered marginally small which is why in this study it is assumed that the SEV has the same efficiency as the BEV without VIPV system.

Table 1: LCA parameters: model assumptions for the reference case.

Parameter	SEV and BEV		Unit
<b>Vehicle weight</b>	1,610		kg
<b>Battery capacity</b>	60		kWh
<b>Battery chemistry</b>	Li-NMC 811		
<b>Vehicle efficiency</b>	9.8		kWh/100 km
<b>Carbon intensity grid-electricity</b>	0.379		kg CO <sub>2</sub> -eq/kWh
<b>WLTP range</b>	615		km
<b>Yearly distance driven</b>	13,000		vkm/yr
<b>GHI</b>	982		kWh/m <sup>2</sup> /yr
	SEV	BEV	
<b>Exterior type</b>	VIPV	regular (without VIPV)	
<b>PV-cell coverage</b>	5	-	m <sup>2</sup>
<b>VIPV-electricity generation</b>	601	-	kWh/yr
<b>Ratio VIPV-electricity : grid-electricity</b>	47% : 53%	0% : 100%	
<b>PV-cell utilization</b>	100%	-	

### 2.3.2 Product system and system boundaries

Two flowcharts have been designed that show the system boundaries of the studied product systems. The chosen system boundary of this study is based on previous EV LCA studies which typically consists of two cycles: the equipment cycle and Well-To-Wheel (WTW) cycle (Nordelöf et al., 2014). The equipment cycle consists of the

material extraction, production, assembly, use and end-of-life of the vehicle. The WTW cycle includes the energy production and vehicle propulsion, which is covered in the electricity generation and electricity conversion phase.

The differences between the systems occur in the production of the vehicle exterior systems (VIPV in the SEV system and regular exterior in the BEV system) and the use-phase of the vehicles. Apart from the exterior production processes, both systems include the same vehicle production processes for the remaining vehicle components such as the glider, battery, electric motor and power train. The first flowchart shows the processes and cut-offs in the SEV system (Figure 6). Normally, the environmental flows are not shown in LCA flowcharts, however, it was chosen to show the inflow of solar energy as it formed a significant part of the electricity generation for the vehicle and also to depict the difference in the use-phase compared to the BEV system. The second flowchart shows the system boundaries of the BEV (Figure 7). Here, the vehicle exterior production consisted of material extraction production of steel body panels and glass windows. In this system there is no inflow of solar energy, which is the difference in use-phase from the SEV system. In both systems a mass allocation procedure was used to deal with the multi functionality issue; the vehicle manufacturing process produced two co-products of which the environmental impacts were assigned to these flows according to their weight.

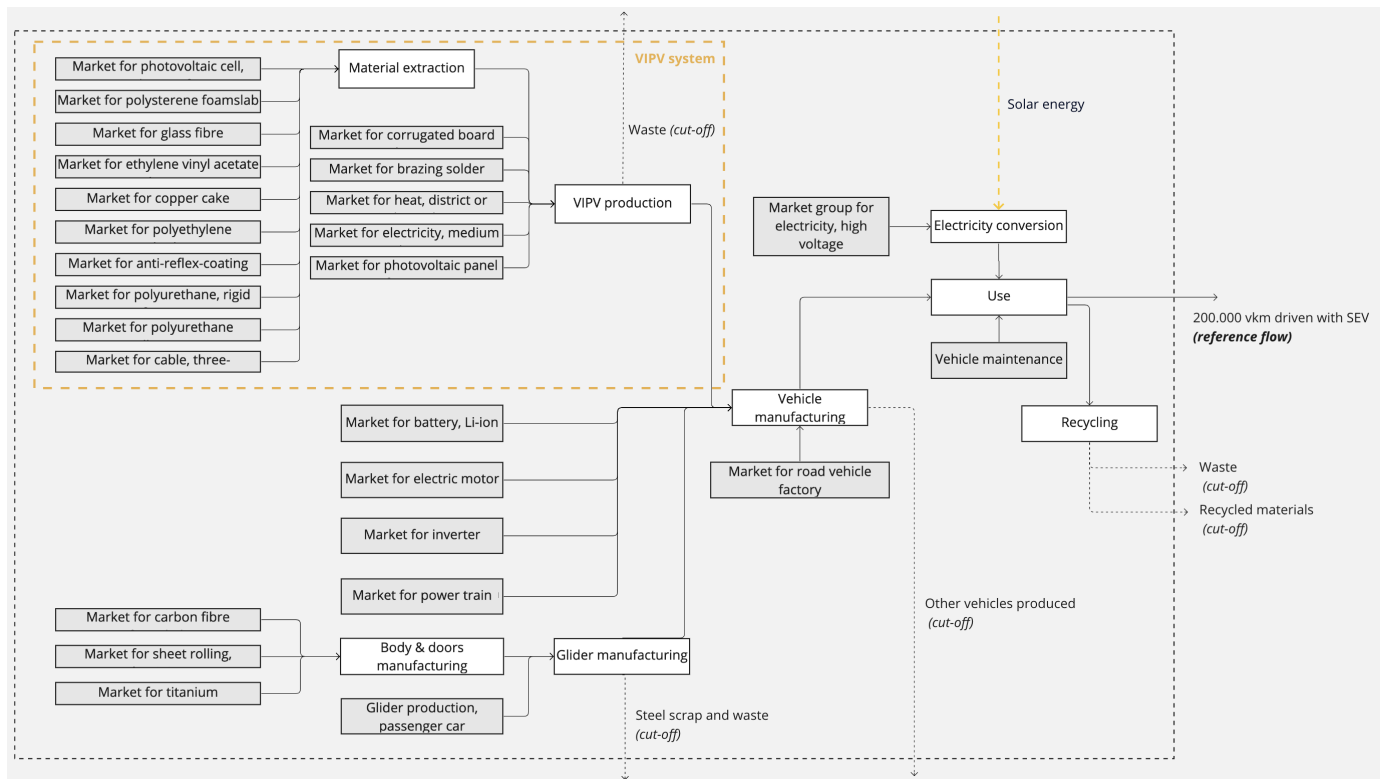


Figure 6: Flowchart of the studied SEV system.

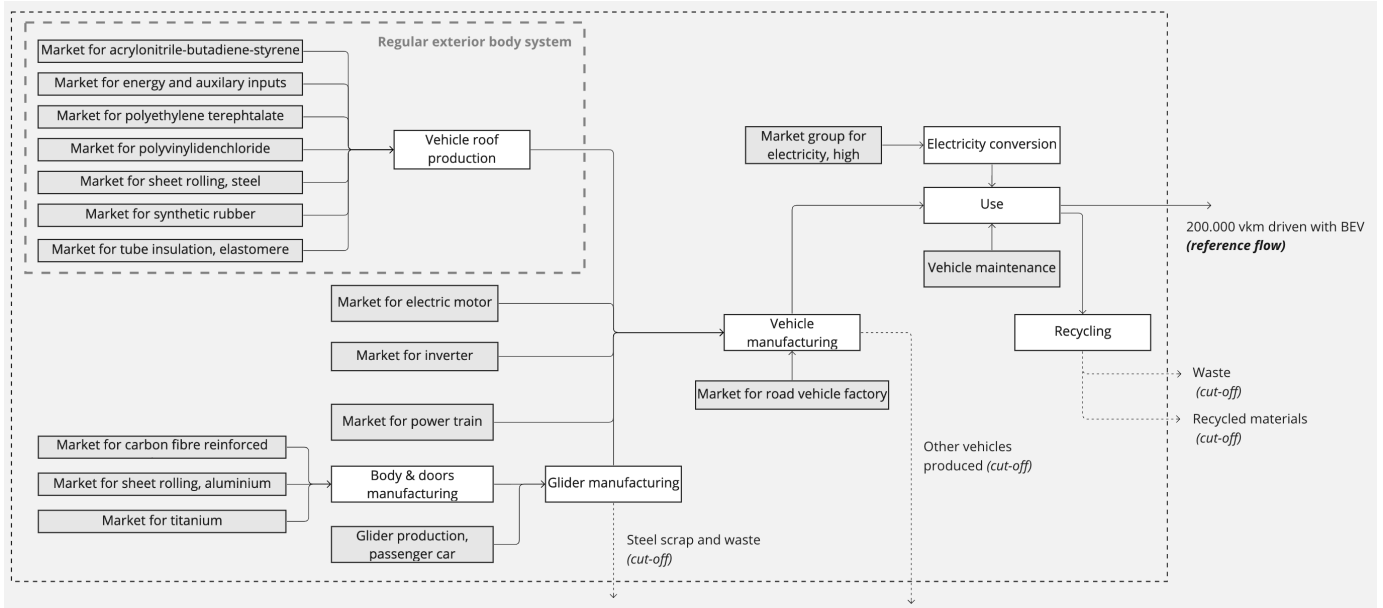


Figure 7: Flowchart of the studied BEV system.

### 2.3.3 Impact assessment method

An LCA can be used to assess different environmental impact categories. In previous EV LCA studies, the focus was mainly set on the CC impact category (Nordelof, 2018). In addition to assessing CC, other impact categories are important to create a complete picture of environmental impacts of an SEV. When solely focusing on CC impacts of EVs, one can easily This LCA study has assessed impact categories from the CML2016 and ReCiPe method, which are commonly used in EV LCA studies (Accardo et al., 2021; Koroma et al., 2022; Mahmud et al., 2019; Temporelli et al., 2020). The CML2016 method is specifically designed to assess environmental impacts of production processes located in Europe. The selected established midpoint indicators are known for their significant contribution in climate impacts in the transport sector: CC, Acidification (AC), Energy Resources (ER), Fossil Depletion (FD) (CML2016) and Metal Depletion (MD) (ReCiPe) (Table 2). MD seemed under-represented in EV studies, however, the PV-cells of the VIPV system and the EV battery require metals like silicon, cobalt and lithium which likely affect the MD impact. Therefore, the MD impact category was selected as part of the impact assessment method.

Table 2: Impact assessment method: chosen impact categories

Impact category	Abbreviation	Unit
Climate change	CC	kg CO <sub>2</sub> -eq
Acidification	AC	kg SO <sub>2</sub> -eq
Energy resources	ER	MJ
Fossil depletion	FD	kg oil-eq
Metal depletion	MD	kg Fe-eq

### 2.3.4 Data collection

The second phase of an LCA study consists of creating an LCI. During this phase, all data is gathered considering the life cycle phases of the two studied vehicle systems. For the LCI, a data collection was made that combined primary data from the vehicle manufacturer and secondary data from literature and existing life cycle inventory databases. The primary data was based on the bill of material from the vehicle manufacturer where the SEV is designed. To ensure that the data collection most closely matched the realistic vehicle systems, it was aimed to collect mostly primary data. When data was not accessible at the vehicle manufacturer due to outsourcing of manufacturing or production processes, it was tried to access this data via its suppliers. If primary data could not be collected within two months, secondary data from literature studies and the ecoinvent v3.8 (Wernet et al., 2021) database was used for the LCI. Ecoinvent is an LCI database that supports various types of sustainability assessments. When subtracting data from this database, it was ensured to pick the processes that were most closely matching the processes of the studied SEV and BEV system.

### 2.3.5 Consistency

Ensuring the consistency between a life cycle assessment and the principles and requirements of ISO14044 is described as a purpose of the critical review procedure (ISO, 2006). Therefore, a consistency check is performed to assess whether the used data is consistent with the LCA approach. During the LCI phase of this LCA study, the scope has been altered to be more consistent with the goal of the study. At first, the scope was set to assess the foreground systems of the entire vehicle, which required data collection of all parts of the vehicle. However, after reiterations it was found that foreground data collection of all vehicle components was not feasible within the set time frame of 2,5 months of data collection. Therefore, ecoinvent v3.8 processes have been used to model the glider, motor and battery of the vehicle.

### 2.3.6 Completeness

This completeness check assesses which the completeness of the data and results of this LCA study. The set system boundary for this study has been defined to include all relevant inputs and outputs that occur between the technological system and the natural environment. To make the LCA results reliable, all significant processes must be included (ISO, 2006). Therefore, the chosen system boundary of this study is based on previous EV LCA studies which typically consists of two cycles: the equipment cycle and well-to-wheel (WTW) cycle (Nordelöf et al., 2014). The equipment cycle consists of the material extraction, production, assembly, use and end-of-life of the vehicle. The WTW cycle includes the energy production and vehicle propulsion, which is covered in the electricity generation and electricity conversion phase. Although the LCI was modelled carefully, data predictions about the end-of-life phase of the VIPV system and the SEV do not capture all the realistically occurring processes. The end-of-life processes are based on generic PV-panel and passenger car recycling of ecoinvent v3.8 processes. These might not include all the current VIPV and SEV recycling processes that will be operated in real life.

## 2.4 Scenario LCA

Now the LCA framework and data collection method have been defined, this section elaborates on the scenario LCA which was performed after the reference case LCA. To estimate a projection of future impacts of an SEV from 2020 until 2050 a prospective LCA has been performed. A prospective LCA creates results as a projection over a certain time, where future perspectives inside the LCI are being integrated. In LCA research this can be done by performing a scenario LCA. A scenario LCA is defined as follows: “ ... a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future.” (Pesonen et al., 2000) To perform such a scenario LCA, a background database is required that projects future scenarios inside an LCA.

For this study, data of an Integrated Assessment Model (IAM) was used to project future scenarios that represent different ranges in CC mitigation. An IAM combines scenarios of societal and economic conditions as well as projections in atmospheric radiative forcing targets. The societal and economic conditions are developed by the IAM community as so-called Shared Socio-economic Pathway (SSP) scenarios (O'Neill et al., 2014). These SSPs provide a structured model to project uncertainties in socio-economic developments. In addition, to describe different trajectories for atmospheric radiative forcing up until 2100 the Representative Concentration Pathway (RCP) have been defined. These RCPs include possible changes in future greenhouse gas emissions and represent different scenarios in atmospheric concentrations (Figure 8).

The IAM data that was used came from *IMAGE*, which is a comprehensive integrated modelling framework of interacting human and natural systems (Stehfest et al., 2014). The *IMAGE* framework is suited for assessments of interactions between human developments and its effects on the natural environment. Additional data of the study of Meide et al. (2022) was used that includes future scenarios on cobalt production. This additional data was useful to model impacts of the studied vehicles as these include Nickel-Manganese-Cobalt (NMC)-811 Lithium-ion (Li-ion) batteries which contain cobalt. The data was used in this study to provide projections of CC impacts with a temporal scale from 2020 up until 2050. The database that was used for the scenario LCI includes the CC scenario SSP2, which is known as the "Middle-of-the-road" pathway. The SSP2 pathway describes developments that are in line with the observations of the past century (Sacchi, Terlouw, et al., 2022). The following RCP scenarios were used in this study (Sacchi, Terlouw, et al., 2022):

- SSP2 - RCP base scenario (RCP 8.5): representing a rising radiative forcing pathway leading to  $8.5 \text{ W/m}^2$  ( $\sim 1370 \text{ ppm CO}_2\text{-eq}$ ) by 2100. This CC scenario corresponds to a trajectory where a continued rise of emissions cause global warming effects of  $\sim 5,0^\circ\text{C}$  by 2100.
- SSP2 - RCP 2.6 scenario, representing a pathway with a peak in radiative forcing at  $\sim 3 \text{ W/m}^2$  ( $\sim 490 \text{ ppm CO}_2\text{-eq}$ ) before 2100 and then declines (van Vuuren et al., 2011). This scenario corresponds to a trajectory that causes  $\sim 1.5$  to  $2^\circ\text{C}$  by 2100.
- SSP2 - RCP 1.9 scenario, representing a pathway leading to  $1.9 \text{ W/m}^2$  that corresponds to a limiting of global warming below  $1.5^\circ\text{C}$  by 2100.

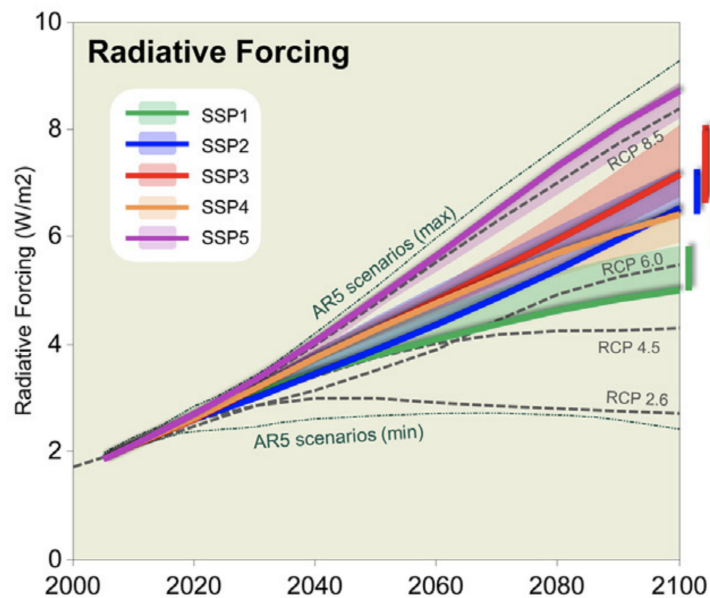


Figure 8: Radiative forcing as projected by the different RCP scenarios (Riahi et al., 2017)

## 2.5 Sensitivity analyses

Alongside the scenario LCA, three different sensitivity analyses were performed to assess the effects of changing one modelling parameter at the time (known as a "what if" analysis). The environmental impacts of the use of an SEV were expected to depend on factors such as vehicle efficiency (kWh/km), GHI (kWh/m<sup>2</sup>/yr) and the driving behavior of the user. As all these factors influence the electricity use of the SEV, which directly relates to the CC impacts of the vehicle. Therefore, it was chosen to model these factors as different parameters in sensitivity analyses. The results could show the most beneficial scenario in terms of CC impacts to drive an SEV. The different created sensitivity cases are listed below.

- *Vehicle efficiency*

The vehicle efficiency affects the amount of required electricity to power the BEV battery. The vehicle efficiency is the amount of energy a vehicle consumes to drive a certain distance (kWh/km) which is dependent on many parameters including power train efficiency, aerodynamic drag, vehicle weight, AC-DC inverter efficiency and rolling resistance. As a VIPV system has a maximum peak capacity per day, the battery of the SEV requires a grid-charge once the battery is out of VIPV generated electricity (VIPV-electricity). Therefore, a VIPV system that is installed on a highly efficient vehicle would require less grid-electricity to drive a certain distance compared to a less efficient vehicle (Figure 9). To assess what the exact effect is of vehicle efficiencies on the CC impacts related to grid-charging, three different efficiency rates have been modelled. The efficiencies that were modelled are the base case of 9.8 kWh/100 km, a 'medium efficiency' of 20 kWh/100 km and a 'low efficiency' of 50 kWh/100 km (Table 4). The base case resembled the realistic efficiency of the studied SEV of which the value is retrieved from the vehicle manufacturer.

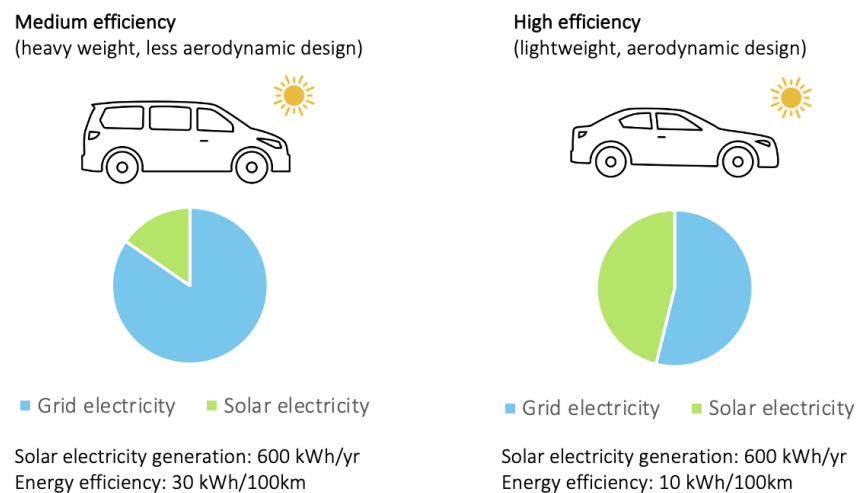


Figure 9: Effect of vehicle energy efficiency on the total share of VIPV-electricity consumed. With an annual production of 600 kWh/yr by the VIPV system and assuming a yearly distance driven of 13,000 km based on an operation phase in the Netherlands.

- *Global horizontal irradiation*

Next to the energy efficiency that influences the CC impacts of the SEV, the GHI is also expected to influence CC impacts. As different geographical locations have different GHI values, the location of operation of the vehicle determines the share of VIPV-electricity and required grid electricity. Three geographical locations have been selected which resemble a relatively high, average and low GHI value compared to the European average (Table 3). The GHI of the base assumption was selected to represent

the European average GHI value of 982 kWh/m<sup>2</sup> which is in Amsterdam (NL). Bergen (NO) was selected for the GHI scenario with a relatively low value of 747 kWh/m<sup>2</sup>, and Zaragoza (ES) as the location with a relatively high GHI value of 1537 kWh/m<sup>2</sup>.

To use these horizontal irradiation levels, the annual electricity generated by the VIPV system defined the share of grid-electricity required. A full lifetime of the modelled SEV operated in Bergen and Zaragoza would generate 462 kWh/yr and 952 kWh/yr respectively. The amount of VIPV-electricity was calculated with the GHI by using the solar panel efficiency (23%) and solar panel yield. When the solar generated electricity per year is known we can calculate the percentage of kilometers driven on VIPV-electricity (Eq. 1). The amount of kilometers that is driven on solar generated electricity can be subtracted from the electricity that would be required from the grid. Thus, the higher the share of VIPV-electricity compared to grid-electricity the lower the amount of grid-electricity required. With the base assumption of an annual distance travelled of 13,000 km, it means that the vehicle requires 1268 kWh each year with the assumed energy efficiency of 9.8 kWh/100 km. To calculate the share of vehicle kilometers driven on VIPV-electricity the following calculation was used:

$$\text{Percentage solar vkm (\%)} = \frac{\text{Annual required electricity (kWh/yr)}}{\text{Annual solar electricity (kWh/yr)}} \quad (1)$$

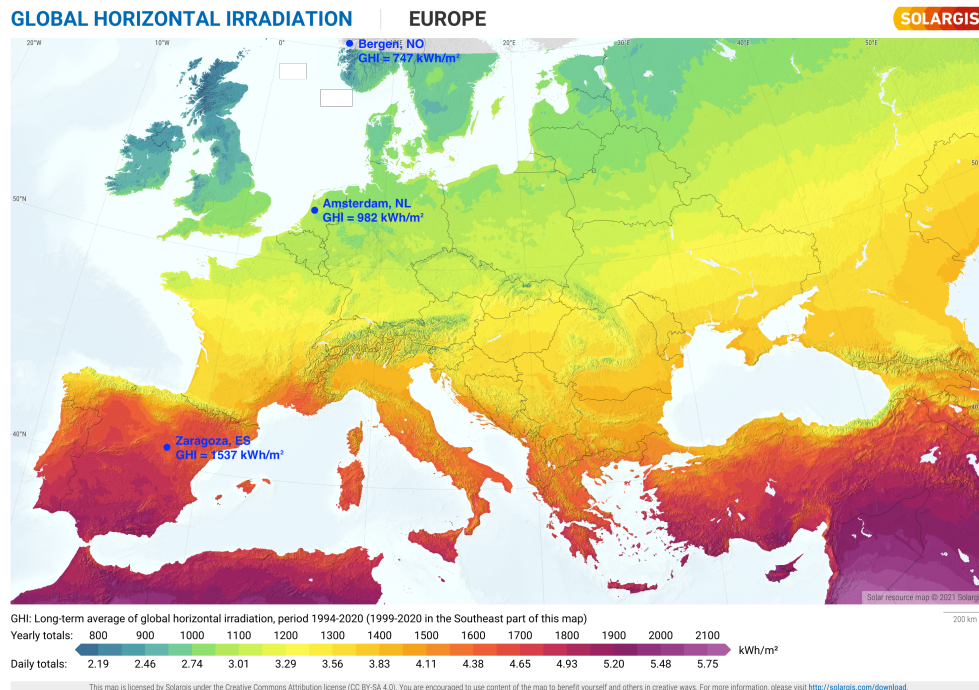


Figure 10: Selection of locations with different GHI values. Three different locations are chosen that resemble a low, middle and high GHI value.

Table 3: Share of distance travelled on VIPV-electricity and required grid-electricity.

Location	Amsterdam, NL	Zaragoza, ES	Bergen, NO	Resource
GHI (kWh/m <sup>2</sup> /yr)	982	1537	747	SolarGis (2022)
Annual VIPV-electricity (kWh/yr)	601	952	462	Calculated
Annual grid electricity (kWh/yr)	668	316	806	Calculated
Share of VIPV-electricity	47%	75%	36%	Calculated

Table 4: Parameter changes of performed sensitivity analyses

Vehicle efficiency cases	Efficiency label	Resource	
9.8 kWh/100 km ( <i>reference case</i> )	High efficiency	Vehicle manufacturer	
20 kWh/100 km	Medium efficiency	Author's estimate	
50 kWh/100 km	Low efficiency	Author's estimate	
GHI cases	GHI	Share of VIPV-electricity	Resource
Amsterdam (NL) ( <i>reference case</i> )	982 kWh/m <sup>2</sup> /yr	47%	SolarGis (2022)
Zaragoza (ES)	1537 kWh/m <sup>2</sup> /yr	75%	SolarGis (2022)
Bergen (NO)	747 kWh/m <sup>2</sup> /yr	36%	SolarGis (2022)
Driving behavior cases	Driving profile	Share of VIPV-electricity	Resource
35.6 km daily	35.6 km/day	44%	Calculated
50 km weekday	50 km/weekday	41%	Calculated
150 km weekend	150 km/weekend	65%	Calculated
400 km weekend	400 km/weekend	26%	Calculated

- *Driving behavior*

The driving behavior influences the share of solar powered kilometers that can be driven with an SEV. The share of distance driven on solar generated electricity depends on the maximum PV-yield of the VIPV system. In this study, the VIPV was assumed to produce a maximum electricity yield of 6.9 kWh per day according to vehicle manufacturer data. When assuming the reference case vehicle efficiency of 9.8 kWh/100 km, the VIPV system was able to generate up to 70 km of electricity per day. Thus, it is expected that there will be a considerable difference in impacts when someone drives an SEV daily for 35.6 km compared to a driving behavior of 150 km on weekend days only. To test the impact of these differences in driving behavior, four different driving profiles have been analysed (Table 4).

The first driving profile was considered as the reference case of this study, which was tried to resemble a Dutch average of 13,000 kilometers driven in a passenger car each year (CBS, 2020). This case was modelled as a driving distance of 35.6 km each day. The *50 km weekday* case was modelled as a 25

km commute on weekdays (50 km round trip). Besides these two cases where the vehicle was driven almost every day for short distances, it was chosen to model two profiles of drivers that only use their vehicle during each weekend for longer trips. This could represent a person that uses any other mode of transportation (public transport, bicycle or by foot) during the week for commuting and other activities. The *150 km weekend* and *400 km weekend* were modelled as weekend travel distances of respectively 150 km and 400 km (round trip) (Table 4). The share of VIPV-electricity was calculated with the total amount of solar electricity generated by the VIPV system (kWh/yr) by the use of a VIPV-calculator model. The total generated electricity was divided by the total amount of required electricity (kWh) for a certain distance (km). The required electricity (kWh) for the distance driven was calculated by multiplying the distance (km) with the vehicle efficiency (kWh/km).

### 3 Life cycle inventory

In the second phase of an LCA study, the LCI is established. This inventory includes a quantified data collection of the inputs and outputs that are relevant in the two assessed vehicle systems (the SEV and BEV). The designed flowcharts show the unit processes that are involved within the defined system boundary that includes all data that is relevant to the cradle-to-gate life cycle phase of the SEV and BEV (Figure 6 and Figure 7). In the following sections, a description of the used parameters and inventory of input and output data is given for the two vehicle systems. The following processes for the SEV and BEV system are discussed hereafter: vehicle components, use-phase, maintenance and end-of-life.

#### 3.1 Vehicle components

The vehicle components included the following: exterior system (VIPV or regular), glider, battery system and electric motor system. The input parameters for the SEV are shown in Table 5. Below, the LCI of each component is discussed, starting with the two different exterior systems, followed by the vehicle components that were included in both systems: glider, battery and electric motor.

Table 5: SEV components.

Category	Component
Glider	Glider
VIPV system	PV panels
Battery system	Battery (high voltage + low voltage) Charger Converter
Electric motor system	Motors Inverter Power distribution unit

#### 3.2 Vehicle exterior: VIPV

The exterior system LCI for the SEV includes all the VIPV components that are required for the integration of PV-panels on the vehicle's exterior. The LCI includes the material extraction, transportation and manufacturing of the PV-panels. The material composition of the VIPV system consists of mono silicon solar cells, plastics, copper and cabling. Characteristics of the PV-panels are shown in Table 7. The VIPV system also requires a small extra battery, however, this extra battery was not included in this analysis as data on the weight of this battery was not clearly defined yet by the vehicle manufacturer. These extra battery materials might have an impact on the environmental impact of the SEV, however, it is important to note that these effects were not taking into account in this analysis.

As specific manufacturing data was not available from the vehicle manufacturer the data on the required manufacturing energy of the PV-panels was based on Krebs-Moberg et al. (2021) and data from theecoinvent v3.8 process of PV-panel production (single-Si wafer). Due to confidentiality agreements, the detailed material compound of the VIPV system cannot be shared publicly (Appendix 21).

Table 6: Life cycle inventory: VIPV system

Output	Amount	Unit	Resource
PV-panel	1	square meter	
Waste plastic	1.69	kg	Vehicle manufacturer
<b>Input</b>			
<i>Product materials</i>			
Photovoltaic cell, single-Si wafer	1	square meter	Vehicle manufacturer
Solar glass	5	square meter	Vehicle manufacturer
Other (PE and cabling)	5.09	kg	Vehicle manufacturer
<i>Manufacturing</i>			
Corrugated card box	1.09	kg	Ecoinvent
Brazing solder	8.7E-3	kg	Ecoinvent
Heat	4.86	MJ	Vehicle manufacturer
Electricity	28.67	MJ	Krebs-Moberg et al. (2021)
Photovoltaic panel factory	4E-6	unit	Ecoinvent

### 3.3 Vehicle exterior: regular

The exterior system LCI for the BEV includes the material extraction, production and manufacturing of a regular vehicle exterior. The regular vehicle exterior was assumed to include steel body panels and glass windows which were based on data of established EVs obtained from the A2MAC1 database (A2MAC1, 2022). In this study, the exterior material compound includes 67.6% steel, 21.3% glass, 5.0% elastomers, 2.8% wire harness, 1.8% acrylonitrile butadiene styrene thermoplastic and 1.5% polypropylene.

Table 7: Life cycle inventory: Regular exterior

Output	Amount	Unit	Resource
Regular exterior	1	unit	
<b>Input</b>			
<i>Product materials</i>			
Steel	33.6	kg	A2MAC1 (2022)
Glass	9.6	kg	A2MAC1 (2022)
Elastomers, EDPM	2.4	kg	A2MAC1 (2022)
Plastics, ABS	0.0864	kg	A2MAC1 (2022)
Plastics, Polypropylene	0.72	kg	A2MAC1 (2022)
Wire harness, tube insulation	0.134	kg	A2MAC1 (2022)
<i>Manufacturing</i>			
Energy and auxiliary inputs	33.6	kg	Ecoinvent

### 3.4 Glider system

The second LCI component is the vehicle glider which consists of all components of the vehicle that are not part of the power train among which the body, doors, chassis, steering, braking and non propulsion related electronics. The light-weighted material of the body and doors of the SEV were collected from the vehicle manufacturer. The remaining weight of the vehicle glider, was adapted from the ecoinvent v3.8 database of a generic passenger vehicle glider.

Table 8: Life cycle inventory: Glider (including body and doors)

<b>Output</b>	<b>Amount</b>	<b>Unit</b>	<b>Resource</b>
Glider	1	unit	
<b>Input</b>			
<i>Product materials</i>			
Glider	861.26	kg	Vehicle manufacturer
Titanium	6.55	kg	Author's estimate
Sheet rolling, aluminium	25.82	kg	Author's estimate
Carbon fibre reinforced plastic	10.8	kg	Author's estimate
<i>Manufacturing</i>			
Road vehicle factory	2.62E-7	unit	Sacchi, Bauer, et al. (2022)

### 3.5 Battery system

The third modelled LCI component of the SEV: the battery system, included a high-voltage Li-ion battery, a low-voltage Li-ion a battery, a charger and a converter. The weights of these components were collected from the vehicle manufacturer. The high-voltage and low-voltage Li-ion batteries were modelled respectively as an NMC-811 Li-ion battery and as a rechargeable Li-ion battery. Data of these batteries was collected from the ecoinvent v3.8 database. Additionally, data of the vehicle charger and converter was collected from ecoinvent v3.8.

Table 9: Life cycle inventory: Battery system

<b>Output</b>	<b>Amount</b>	<b>Unit</b>	<b>Resource</b>
Battery system	1	unit	
<b>Input</b>			
<i>Product materials</i>			
Li-NMC battery	350	kg	Vehicle manufacturer
Battery, Li-ion rechargeable	24.94	kg	Vehicle manufacturer
Charger, electric passenger car	12.7	kg	Vehicle manufacturer
Converter, electric passenger car	3.46	kg	Vehicle manufacturer

### 3.6 Electric motor system

The fourth LCI component: the electric motor system, included an electric motor, an inverter and a power distribution unit. The weights of these components were collected from the vehicle manufacturer of the SEV. Then, LCI data of the electric motor, the inverter and power distribution unit were collected from the ecoinvent v3.8 database (Table 10).

Table 10: Life cycle inventory: Electric motor

<b>Output</b>	<b>Amount</b>	<b>Unit</b>	<b>Resource</b>
Electric motor system	1	unit	
<b>Input</b>			
<i>Product materials</i>			
Electric motor	165.6	kg	Vehicle manufacturer
Inverter	15.7	kg	Vehicle manufacturer
Power distribution unit	52.45	kg	Vehicle manufacturer

### 3.7 Vehicle use-phase

The use-phase LCI of the modelled vehicles consisted of charging the vehicle with electricity. For the SEV, this included a ratio of VIPV-electricity : grid-electricity. For the BEV the use-phase consisted solely of grid-electricity. For PV-charging, it was assumed that all incoming horizontal irradiance was used by the VIPV either directly by on-board charging during driving or either by charging the battery while the vehicle is at a stationary position. No emissions were related to PV-charging. For grid-charging, the average 2020 EU electricity mix was used from ecoinvent v3.8, which emitted 0.379 kg CO<sub>2</sub>-eq/kWh.

Another factor which influenced the grid-electricity use of the vehicle charging is the charging efficiency of the battery. Due to electricity conversion from AC-DC charging, there occur charging losses, which in this study is assumed as a 15% charging loss. When taking charging losses into account, the vehicle required 1.127 kWh/km (Table 11).

Table 11: Life cycle inventory: Use-phase

<b>Output</b>	<b>Amount</b>	<b>Unit</b>	<b>Resource</b>
Distance driven	1	km	
<b>Input</b>			
<i>Product materials</i>			
Electricity, high voltage	1.127	kWh	Vehicle manufacturer

### 3.8 End-of-life and maintenance

The end-of-Life LCI of the SEV and BEV included treatment and recycling processes of the vehicle glider and the Li-ion battery. For the SEV, the end-of-life of the VIPV system included treatment of the PV modules. Data on these processes was adapted from ecoinvent v3.8. During the life time of the vehicle it was assumed that regular maintenance was required. The vehicle maintenance data was collected from ecoinvent v3.8 (Table 12).

Table 12: Life cycle inventory: End-of-life and maintenance

<b>Output</b>	<b>Amount</b>	<b>Unit</b>	<b>Resource</b>
Treatment of used glider	1127	kg	Vehicle manufacturer
Treatment of used Li-ion battery	262.5	kg	Vehicle manufacturer
Maintenance passenger car	1	unit	Ecoinvent
Treatment c-Si PV module	10.3	kg	Vehicle manufacturer

# RESULTS

**Integrated PV-panels on the exterior body of an SEV.**

Source: Sonosmotors (2022)



## 4 Results

In this section, the results of the reference case LCA, the scenario LCA and sensitivity analyses are shown. Starting with the characterisation step which shows the impacts for the SEV and BEV in the chosen impact categories. Then, a contribution analysis shows the contribution of the different life cycle phases. Next, the scenario LCA was performed to show the influence of different CC mitigation scenarios. Lastly, the different proposed sensitivity analyses were performed to investigate the effect of vehicle efficiency, GHI and driving behavior.

### 4.1 Characterisation

A characterisation step is the part of an LCA study where all results are multiplied by a factor that reflects their relative contribution in an environmental impact category. It quantifies how much impact the studied alternative has in each impact category. The characterisation results showed the total impacts for the defined functional unit of 200,000 vkm distance driven by the vehicle (shown in the bottom column of Table 13). To enable direct comparison to other study results that report on (S)EV LCA, an additional functional unit of 1 vkm was created of which the results are shown in Table 14.

The results for the total lifetime of the vehicle in the bottom column showed that the SEV had less impacts than the BEV in all impact categories except for metal depletion with the functional unit of 1 vkm (Table 14). For the use-phase and end-of-life phase the SEV resulted in less environmental impacts than the BEV. However, the production of the regular exterior has decreased impacts in all assessed impact categories compared to the impacts of the production of VIPV. This means that the SEV caused more environmental impacts in its production phase. Thus, the BEV is less impacting than the SEV right after the vehicles have been produced. It is due to the low impacts during the use-phase of the SEV that the cradle-to-grave environmental impacts were lower than the BEV.

Table 13: Characterisation results for the functional unit of 200,000 vkm. Production related impacts of the vehicle components is the same for both vehicles (in grey). The total results combines all impacts of production, use and end-of-life for 200,000 vkm. For each life cycle phase the lowest impact category result is shown in green.

Impact category	CC	AC	ER	FD	MD
Unit	kg CO <sub>2</sub> -eq	kg SO <sub>2</sub> -eq	MJ	kg oil-eq	kg Fe-eq
Production vehicle components (excl. exterior)	1.71E+04	1.59E+02	2.01E+05	5.18E+03	22,702.67
Production VIPV	1.48E+03	7.92	1.78E+04	4.59E+02	2.52E+02
Production regular exterior	2.48E+02	1.56	2.89E+03	7.44E+01	3.03E+02
Use-phase SEV	4.52E+03	2.07E+01	5.22E+04	1.34E+03	7.14E+01
Use-phase BEV	8.51E+03	3.90E+01	9.82E+04	2.52E+03	1.34E+02
End-of-life SEV	1.95E+03	6.80	1.98E+04	5.10E+02	1.49E+02
End-of-life BEV	1.98E+03	6.84	1.99E+04	5.13E+02	1.49E+02
Total SEV	2.51E+04	1.95E+02	2.91E+05	7.52E+03	2.32E+04
Total BEV	2.78E+04	2.07E+02	3.22E+05	8.29E+03	2.33E+04

Table 14: Characterisation results for the functional unit of 1 vkm. Production related impacts of the vehicle components is the same for both vehicles (in grey). The total results combines all impacts of production, use and end-of-life for 1 vkm. For each life cycle phase the lowest impact category result is shown in green.

Impact category	CC	AC	ER	FD	MD
Unit	kg CO <sub>2</sub> -eq	kg SO <sub>2</sub> -eq	MJ	kg oil-eq	kg Fe-eq
Production vehicle components (excl. exterior)	8.55E-02	7.97E-04	1.00E+00	2.59E-02	1.14E-01
Production VIPV	7.41E-03	3.96E-05	8.90E-02	2.30E-03	1.26E-03
Production regular exterior	1.24E-03	7.82E-06	1.44E-02	3.72E-04	1.52E-03
Use-phase SEV	2.26E-02	1.04E-04	2.61E-01	6.70E-03	3.57E-04
Use-phase BEV	4.26E-02	1.95E-04	4.91E-01	1.26E-02	6.72E-04
End-of-life SEV	9.75E-03	3.40E-05	9.88E-02	2.55E-03	7.44E-04
End-of-life BEV	9.92E-03	3.42E-05	9.93E-02	2.56E-03	7.45E-04
Total SEV	1.26E-01	9.76E-04	1.46	3.76E-02	1.16E-01
Total BEV	1.39E-01	1.03E-03	1.61	4.15E-02	1.16E-01

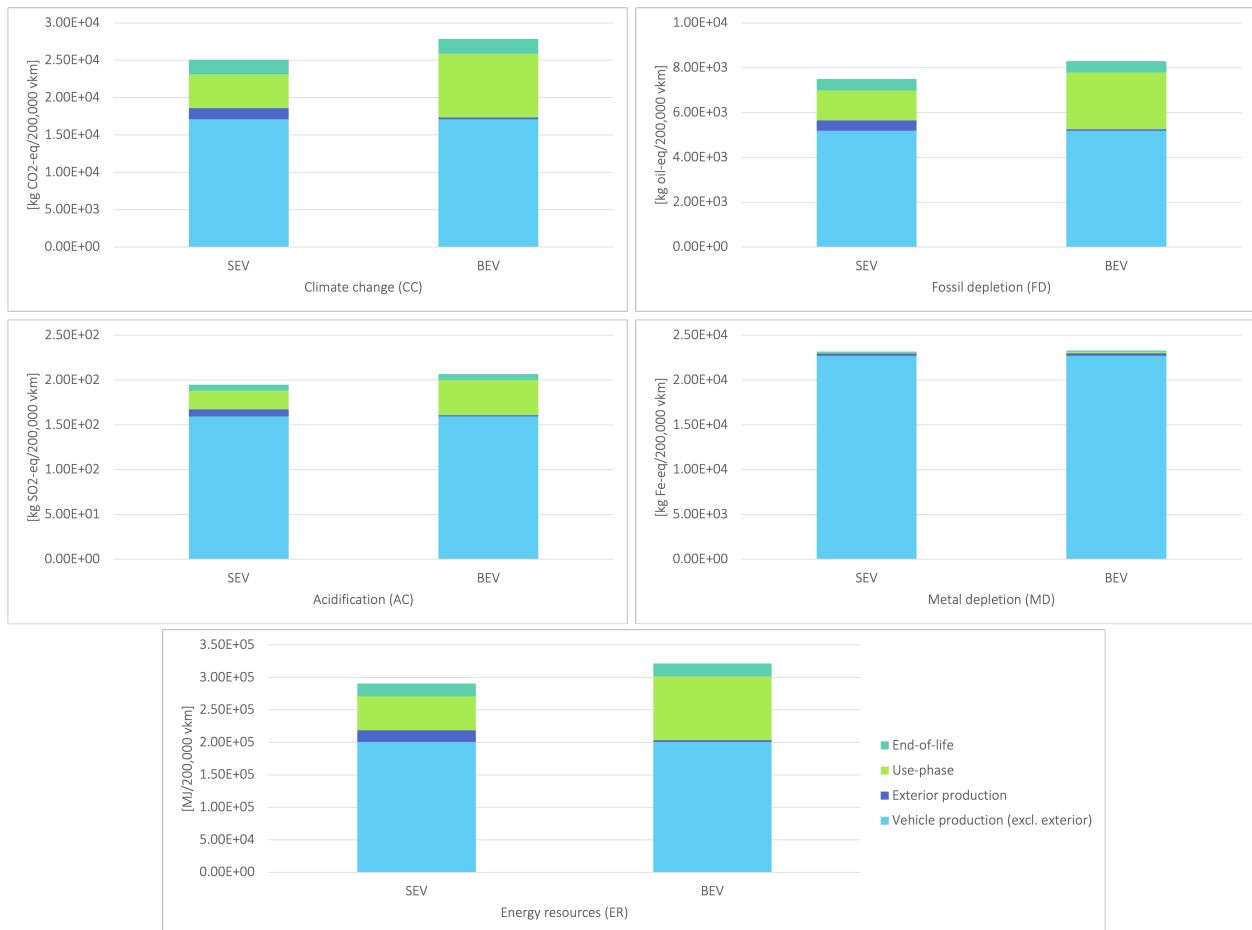


Figure 11: Environmental impact results of the SEV and BEV for the functional unit of 200,000 vkm.

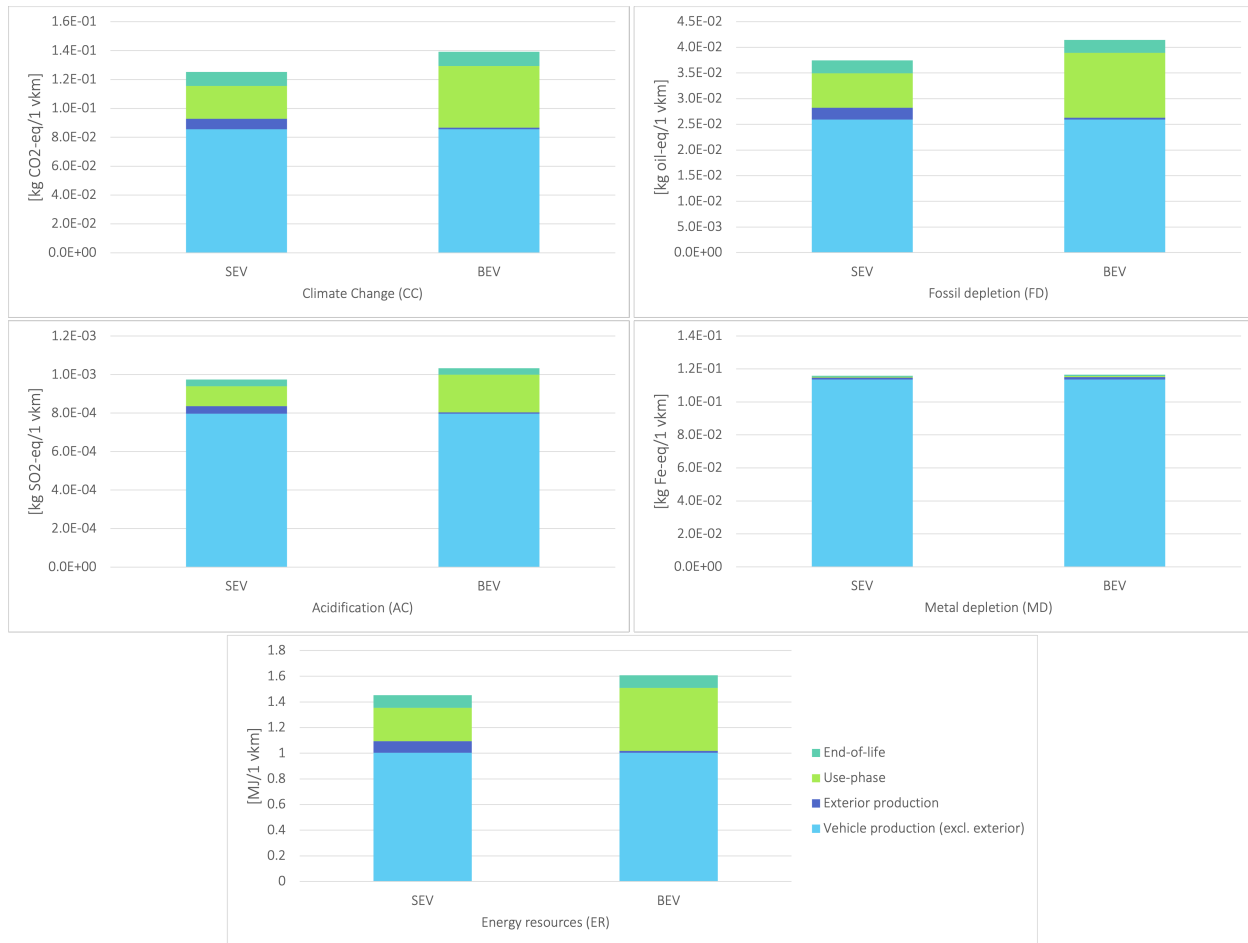


Figure 12: Environmental impact results of the SEV and BEV for the functional unit of 1 vkm.

#### 4.1.1 Contribution analysis

The impact results in each impact category are additionally shown in bar-graphs to enhance easy interpretation of the results. It is shown that the vehicle production phase was the biggest contributor to the environmental impacts of the SEV and BEV (Table 13 and 14). As the SEV and BEV have been modelled with similar LCI data on the vehicle glider (excluding the exterior) the impacts of the vehicle production phase are the same for both vehicles. The differences on which this study focused on are the production of the two exteriors (VIPV and regular) and the use-phase. Before diving deeper into the contributing life-cycle phases in each impact category, a short clarification on which processes were included in the depicted life cycle phases:

- *Production of vehicle components*: this phase included the material extraction, production and assembly of the vehicle components (excluding the VIPV and exterior materials).
- *Production VIPV system and regular exterior*: this phase included the material extraction, production and assembly of the VIPV system (for the SEV) and regular exterior (for the BEV).
- *Use-phase*: this phase included the electricity generation and vehicle charging.
- *End-of-life*: this phase included the recycling efforts and maintenance of the vehicle (for both SEV and BEV) and the recycling of the VIPV system (for the SEV) and the recycling of the regular exterior (for the BEV).

#### *Acidification impacts*

For the functional unit of 200,000 vkm results showed a total AC impact of 195 kg SO<sub>2</sub>-eq for the SEV and 207 kg SO<sub>2</sub>-eq for the BEV. The biggest contributor was the vehicle component production phase, followed by the use-phase. For the SEV, the production of the VIPV had more AC impacts (7.92 kg SO<sub>2</sub>-eq) than the production of the regular exterior for the BEV (1.56 kg SO<sub>2</sub>-eq).

#### *Energy resources impacts*

For the functional unit of 200,000 vkm results showed a total ER impact of 291,000 MJ for the SEV and 322,000 MJ for the BEV. With the vehicle production phase as the biggest contributor, followed by the use-phase. The production of VIPV (17,800 MJ) again caused more impacts than the production of the regular exterior (28,900 MJ).

#### *Fossil depletion impacts*

For the FD impact category, the main contributor was the vehicle component production phase. The use-phase contributed for 18% of the FD impacts for the SEV and for 30% of the FD impacts for the BEV. As the use-phase consisted of grid-charging, the fossil fuel density of the grid determined the FD impacts of the use-phase. When another electricity grid would be used with a higher share of renewable energy sources, the FD impacts would probably be more low.

#### *Metal depletion impacts*

The MD impacts were particularly high in the vehicle components production phase, which accounted for 98% for both SEV and BEV. This was probably due to the use of several metals in the vehicle components including the Li-ion battery and electric motor. The production of the regular exterior was not contributing to the metal depletion of the BEV in a large extent (less than 1%). The same holds for the production of VIPV. This result can be explained as the VIPV and regular exterior are relatively light in weight compared to the weight of all other vehicle components. The 5 m<sup>2</sup> VIPV and regular exterior weigh 59 kg and 47 kg respectively, which were both less than 1% of the total vehicle weight of 1610 kg.

#### *Climate change impacts*

When looking to the contributing life cycle phases in the CC impacts category, results showed that the use-phase was the second largest contributor. This could be expected as the use-phase included driving for 200,000 vkm which required 1.127 kWh/km. However, the contribution of the use-phase of the SEV was less big compared to the BEV, which was due to the PV-cells in the VIPV system that generated electricity to charge the battery. The electricity generation of the VIPV system enabled the SEV to require less grid-electricity compared to the BEV. This lead to a reduction of electricity-grid related impacts. As the BEV was solely dependent on charging from the electricity grid, the fossil-fuel density of the grid directly effected the CC impact of the BEV charging. The third largest contributor was the end-of-life of the vehicles. Where the end-of-life of the SEV (1,950 kg CO<sub>2</sub>-eq) was slightly less impacting than the end-of-life of the BEV (1,980 kg CO<sub>2</sub>-eq), which is due to the regained value of recycled PV-cells of the VIPV system.

The fourth contributor was the production of the vehicle exteriors, which was where the SEV scores worse compared to the BEV. These higher impacts for the SEV were related to the production of its VIPV system. The specific VIPV materials such as the PV-cells, require more manufacturing energy than the regular exterior manufacturing. A more in-depth analysis in AB on the processes that contribute to the impacts of the VIPV production, showed that most impacts (79.4%) come from the single crystalline silicon (single-Si) PV-cell production. The market for silicon production was responsible for 53.2% of the impacts from the production of the VIPV system. Besides the demand for VIPV materials that require energy intensive production processes, the manufacturing of the VIPV system itself required energy intensive processes as well. While the production of the regular exterior was part of the vehicle body production, the production of VIPV consisted of high-precision

cutting, testing of PV-cell efficiency and lamination processes which all required a substantial amount of energy. This explains why the production of the VIPV resulted in more CC impacts than the regular exterior.

The end-of-life showed slightly similar results for the SEV compared to the BEV (Figure 11). An analysis in AB showed that most of the CC impacts come from vehicle maintenance (55.1%) and waste treatment of the vehicle glider (34.1%).

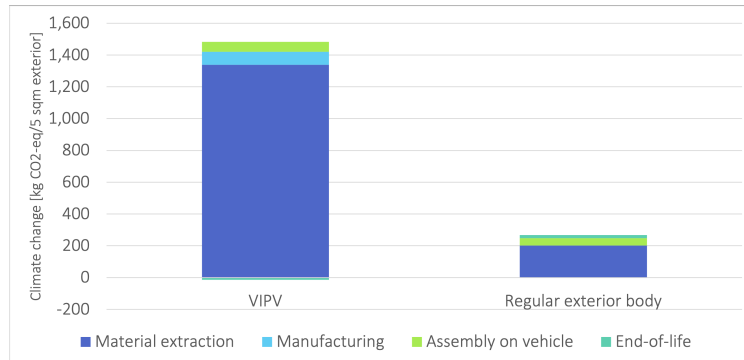


Figure 13: Contributions of life cycle phases of 5 m<sup>2</sup> VIPV and 5 m<sup>2</sup> of regular exterior.

#### *VIPV and regular exterior*

Another analysis was performed to assess the contributions of the different life cycles where we zoom in on the life cycle phases of the VIPV and the regular exterior. As the VIPV system caused more impacts compared to the regular vehicle exterior, assessing where these increased impacts come from helps to identify possibilities to reduce these impacts. This analysis showed the life cycle phases that contribute to the CC impacts of 5 m<sup>2</sup> VIPV and 5 m<sup>2</sup> regular exterior of the following life cycle phases: material extraction (including PV-cell production), manufacturing, assembly on vehicle and recycling.

Results show that the main impacts from the VIPV occurred in the material extraction phase, which accounted for 1,340 kg CO<sub>2</sub>-eq per 5 m<sup>2</sup> of VIPV (Figure 13). The material extraction for the regular exterior caused 200 kg CO<sub>2</sub>-eq per 5 m<sup>2</sup> of exterior, which is only 15% of the impacts that are caused by VIPV material extraction. Thus, the potential to reduce CC impacts from the VIPV seems to be the highest in the material extraction phase. The other contributing phases in the VIPV system were the manufacturing (82.0 kg CO<sub>2</sub>-eq) and the assembly of 5 m<sup>2</sup> VIPV on the vehicle (62.0 kg CO<sub>2</sub>-eq). Which is substantially lower than the impacts coming from the material extraction. This can be explained as the material extraction phase of the VIPV system included the production of the PV-cells that required an energy intensive production process. An analysis in AB showed that the single-Si wafer production (which are material components of the PV-cells) accounted for 70.8% of the CC impacts from VIPV material extraction. The VIPV production impacts were related to the energy that is required for different lamination steps that were performed to attach the PV-cells together to form the VIPV panel.

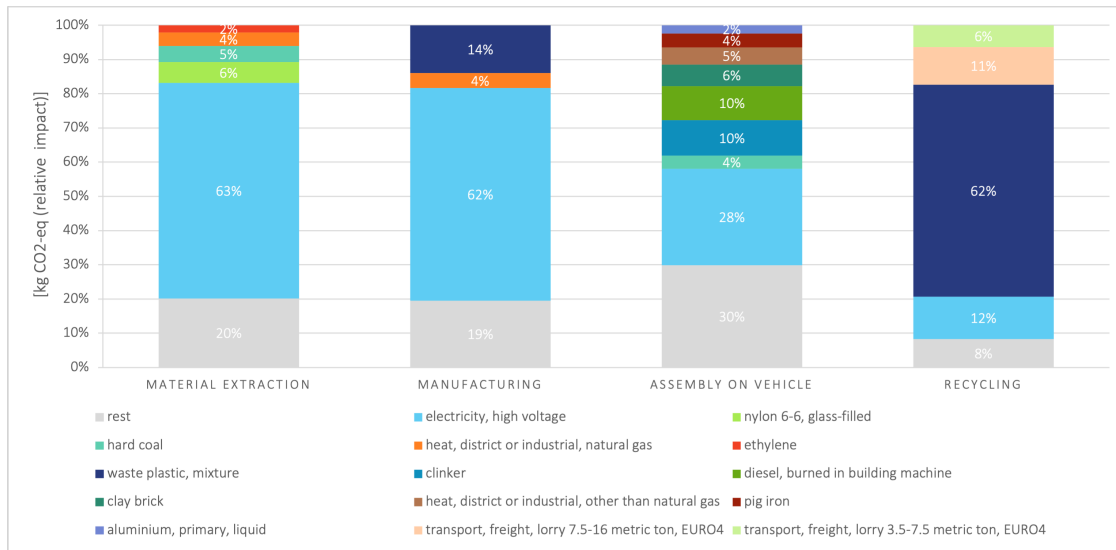


Figure 14: Relative contributions of processes in the life cycle phases of the VIPV system.

#### *Processes in life cycle phases of VIPV*

In order to identify the potential sustainable performance of the VIPV system, an analysis was performed to assess which processes contribute to impacts of the VIPV system. Results showed that electricity use was the biggest contributing process in the material extraction and manufacturing phase of the VIPV system.

In the material extraction phase, the electricity use was responsible for 63% (840 kg CO<sub>2</sub>-eq) of the impacts (Figure 14). This indicates that the production of materials required for the VIPV system demands a substantial amount of electricity use. The production of PV-cells, which were included in the material extraction phase, caused 85% (1,140 kg CO<sub>2</sub>-eq) of the CC impacts in the material extraction phase (Figure 14). The PV-cell impacts are related to the single-Si wafer production that is dependent on the energy (electricity and heat) intensive production of silicon. Therefore, the biggest impact reductions of VIPV materials can potentially be made at reducing the PV-cell related impacts.

For the manufacturing of the VIPV, the electricity use accounted for 62% (51 kg CO<sub>2</sub>-eq) of the impacts. This electricity was used to manufacture the PV-panels of the VIPV system. This process involved the alignment and placement of the PV-cells on the panels, oven lamination and soldering of electronics into the panels. Therefore, to potentially reduce manufacturing impacts the reduction of electricity use impacts could create a substantial result.

## 4.2 Scenario LCA: CC mitigation scenarios

A scenario LCA was performed to investigate the effect of the different CC scenarios (as mentioned in Section 2) on the CC impacts of the SEV and BEV. The scenarios were applied to the functional unit of 200,000 vkm distance driven with the vehicle. In addition, the effect of the CC mitigation scenarios on the CC impacts of the exterior production (VIPV and regular) was assessed separately.

The first analysis assessed the effect of CC scenarios on the impacts of the functional unit of 200,000 vkm. The scenario LCA shows that the RCP 2.6 and RCP 1.9 scenario created strong declines in impacts for both the SEV and BEV (Figure 15). This result can be explained as the more ambitious CC scenarios include LCI data that have a lower carbon-intensity due to an increased share of renewable energy sources in the electricity grid. Thus, the CC impacts of charging (kg CO<sub>2</sub>/kWh) decreased parallel to the growth of ambition in CC mitigation.

This created less CC impacts in the use-phase of vehicles, which suggests that successful implementation of CC policies would positively effect the decrease of CC impacts of both SEV and BEV.

An interesting result was the outcome of the RCP 1.9 scenario, which showed a trend in which the difference between the CC impacts of the SEV and the BEV became smaller over time. The more ambitious RCP 1.9 scenario predicts a relatively low concentration of carbon in the atmosphere that is partly due to the lowering carbon intensity of the electricity-grid. Thus, a low-carbon electricity grid (in the RCP 1.9 scenario) made the CC impact difference between the two vehicles smaller. In that scenario, the grid-charged electricity for both vehicles consisted of a higher share of renewable energy sources where both vehicles benefit from. In that case, both SEV and BEV have access to renewable-based electricity which was where the differences in use-phase CC impacts started to decline.

A second analysis was done to assess the effects of the scenarios on the CC impacts of the two exteriors (VIPV and regular). Results showed that the different RCP scenarios have a bigger influence on the CC impacts of the production phase of VIPV than on the regular exterior (Figure 15). This is probably due to the energy intensive production phase of the VIPV, which lowered in CC impacts when the used electricity came from renewable energy sources. Thus, future changes in fossil fuel based electricity grids will influence the CC impact of VIPV production. This explains why the baseline scenarios depicted a smaller decrease in CC impacts, as the electricity grid was more dependent on fossil fuel use than in the RCP 2.6 and RCP 1.9 scenarios. Thus, the lowest CC impacts of VIPV production can be achieved by the implementation of ambitious CC mitigation measures. In addition, these results imply that future projections of SEV CC impacts are depending on these measures and therefore highly uncertain.

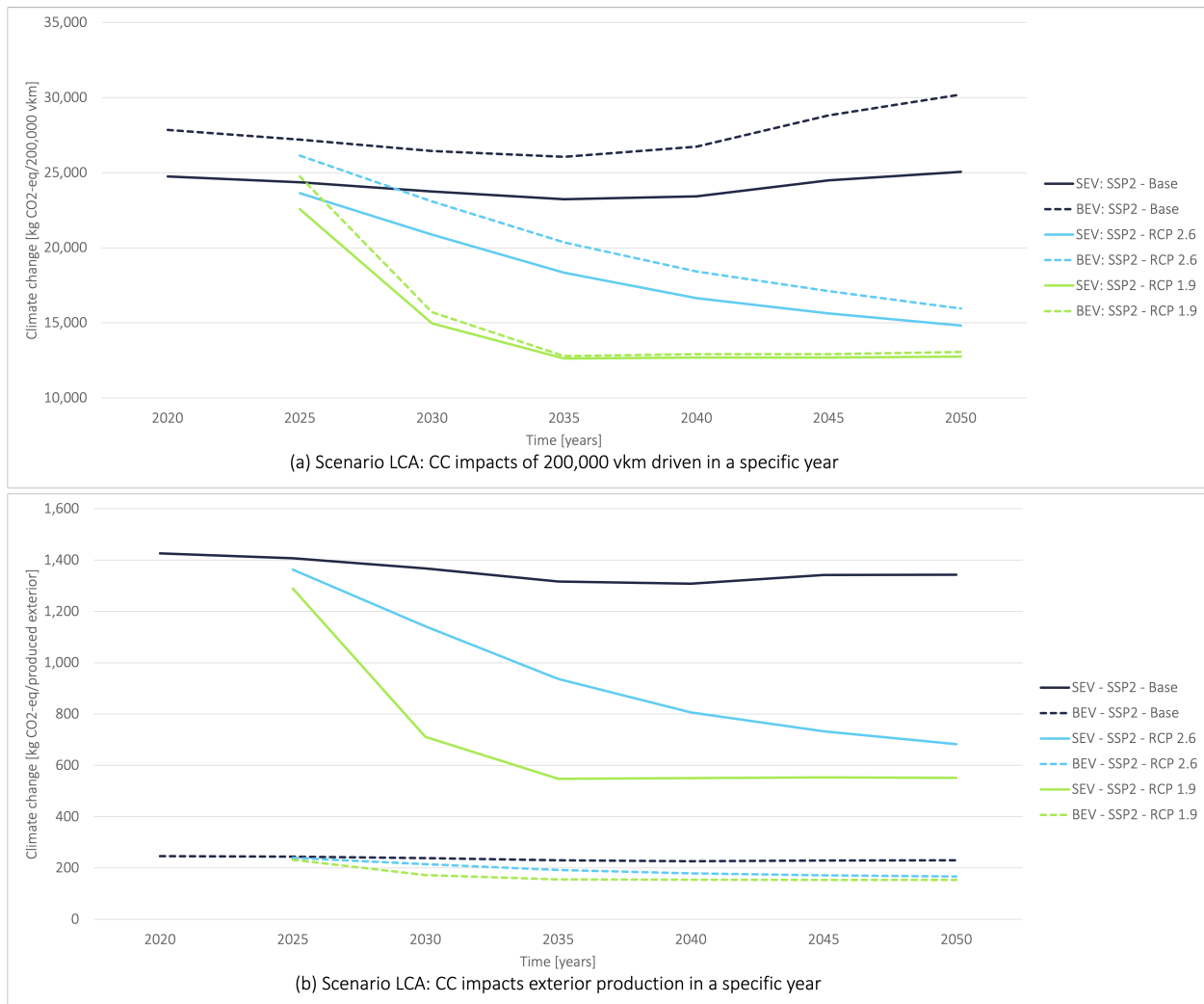


Figure 15: Scenario LCA results for CC impacts of the functional unit of 200,000 vkm the production of the vehicle exterior (VIPV for SEV and regular exterior for BEV). With CC scenarios SSP2 - Base, SSP2 - RCP 2.6 and SSP2 - RCP 1.9.

### 4.3 Sensitivity analyses

In this section, the three proposed sensitivity analyses are performed. The effect was analysed of changing the parameters in vehicle efficiency, GHI and driving behavior on the impacts of the SEV and BEV. The sensitivity analysis have been performed for the CC impact category, as this category is most influenced by the parameter changes and as this category is important to assess the carbon emission mitigation potential of SEVs. Alongside the parameter changes in the foreground systems of the vehicles, a set of additional parameters was changed: increase in grid-efficiency each year (0.01 kg CO<sub>2</sub>-eq/yr) and decrease in PV-panel efficiency each year (0.01%/yr). These have been changed in order to incorporate developments in grid-electricity mixes and decrease of PV-cell efficiency after each year of operation. Therefore, it must be noted that the total CC impact results of the sensitivity analyses are different from the static LCA results as these sensitivity analyses include parameter changes over time.

### 4.3.1 Vehicle efficiency

Results of the different vehicle efficiencies showed that a more efficient use of electricity results in lower CC impacts during the use-phase of the SEV and BEV (Figure 16). The cradle-to-gate phase (or production phase) of the SEV created more CC impacts than the production of the BEV. This is due to the increased CC impacts of VIPV production compared to the regular exterior production of the BEV. For each modelled efficiency pair, the break-even point occurred at the same point at 79,000 vkm (6.1 years of operation when assuming 13,000 vkm/yr) for the SEV and BEV. This happened as both vehicles were affected by the same efficiency factor. The SEV and BEV with an efficiency of 9.8 kWh/100 km each used the same amount of electricity to drive one kilometer. As the VIPV system of the SEV was assumed to generate 601 kWh each year, this amount of electricity was not required from grid-charging. Thus, while the SEV charged its battery with VIPV-electricity, the BEV had to charge all its required electricity from the grid. This explains the increased slope of kg CO<sub>2</sub>-eq for the BEV compared to the slope of the SEV (Figure 16). Before the break-even point, where the SEV starts to have less CC impacts than the BEV (at 79,000 vkm), the CC impacts of the SEV are higher than the BEV (Figure 16).

Interestingly, the effect of vehicle efficiency seemed to have a more constant influence on the use-phase CC impacts than replacing a regular exterior with VIPV. Where the addition of a VIPV system had limited capacity to deliver VIPV-electricity to the vehicle, the vehicle efficiency had a constant effect on the amount of required electricity to charge the vehicle. The use-phase CC impacts of an SEV with a vehicle efficiency of 20 kWh/100 resulted in 9,420 kg CO<sub>2</sub>-eq and for the SEV with 9.8 kWh/100 km it resulted in 3,140 kg CO<sub>2</sub>-eq after a use-phase of 200,000 vkm. This is a decrease in use-phase CC impacts of 67%. As the vehicle efficiency directly impacted the required electricity of the vehicle, improving this efficiency had a constant effect on CC impact reductions. While in comparison, the VIPV could provide a maximum of 601 kWh/year, which in this study resulted in a use-phase CC impact decrease of 2,830 kg CO<sub>2</sub>-eq with a functional unit of 200,000 vkm. Thus, depending on the vehicle efficiency of the vehicle, the VIPV had a limited capacity to decrease CC impacts of the use-phase. The higher the efficiency of the vehicle, the higher the share of VIPV-electricity in the ratio of VIPV-electricity:grid-electricity. When vehicle efficiency worsened, the relative effect of VIPV in reduction of use-phase CC impacts decreased (Table 15).

Realistically, most established BEVs have an efficiency of 20 kWh/100 km rather than 9.8 kWh/100 km. Hence, if one would compare the highly efficient SEV (9.8 kWh/100 km) with a moderately efficient BEV (20 kWh/100 km), results showed that the break-even point would occur more early at approximately 24,000 vkm (< 2 years of operation).

Table 15: Effects of VIPV on use-phase CC impacts on vehicles with different efficiencies.

	BEV	SEV	Difference [kg CO <sub>2</sub> -eq]	Reduction [%]
Efficiency [kWh/100 km]	9.8	9.8		
CC impacts use-phase [kg CO <sub>2</sub> -eq]	5,970	3,140	-2,830	-47%
Efficiency [kWh/100 km]	20	20		
CC impacts use-phase [kg CO <sub>2</sub> -eq]	12,200	9,420	-2,830	-23%
Efficiency [kWh/100 km]	50	50		
CC impacts use-phase [kg CO <sub>2</sub> -eq]	30,600	27,800	-2,830	-9%

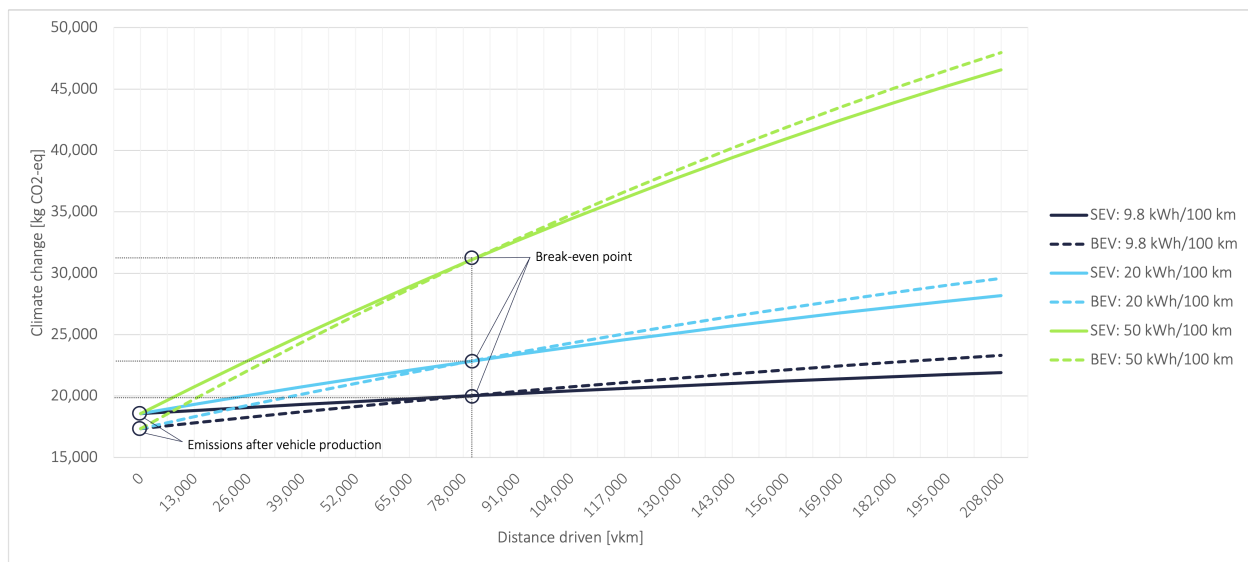


Figure 16: Effects of different vehicle energy efficiencies on CC impact of the SEV and BEV projected over distance driven.

#### 4.3.2 Global horizontal irradiation

As aforementioned, the GHI (depending on the geographical location) value determines the amount of electricity that can be generated by the VIPV system to charge the vehicle battery. This parameter was changed in this sensitivity analysis of which the results showed that the GHI value has a significant effect on the CC impact of the SEV (Figure 17). With that, the GHI influenced the point in time where the break-even occurs between the use-phase of the SEV and BEV.

When the SEV was operated in an area with a GHI of 1,537 kWh/m<sup>2</sup> (Spain), a break-even point between the SEV and BEV occurred at roughly 50,000 vkm. For the GHI values of the Netherlands and Norway, the break-even points occurred at 79,000 vkm and 108,000 vkm respectively (Figure 17). The use-phase of the BEV required more grid-charging from the electricity grid, which is why the impacts of the BEV showed a steeper increase than the impacts of the SEV. However, the results only showed the effect of changes in GHI values and did not resemble the actual carbon intensities of the related local electricity grid. In this analysis, the average grid electricity of Europe was taken as an input from ecoinvent v3.8 that had an impact of 0.38 kg CO<sub>2</sub>-eq/kWh. For

Norway specifically, where the electricity grid runs mostly on renewable power, the impacts will realistically be less worse than depicted in this sensitivity analysis. To conclude, the use-phase CC impacts of the SEV relate to the GHI value in which the vehicle is operated where a higher GHI value increases the share of electricity charged by VIPV and decreases the share of electricity required from the grid.

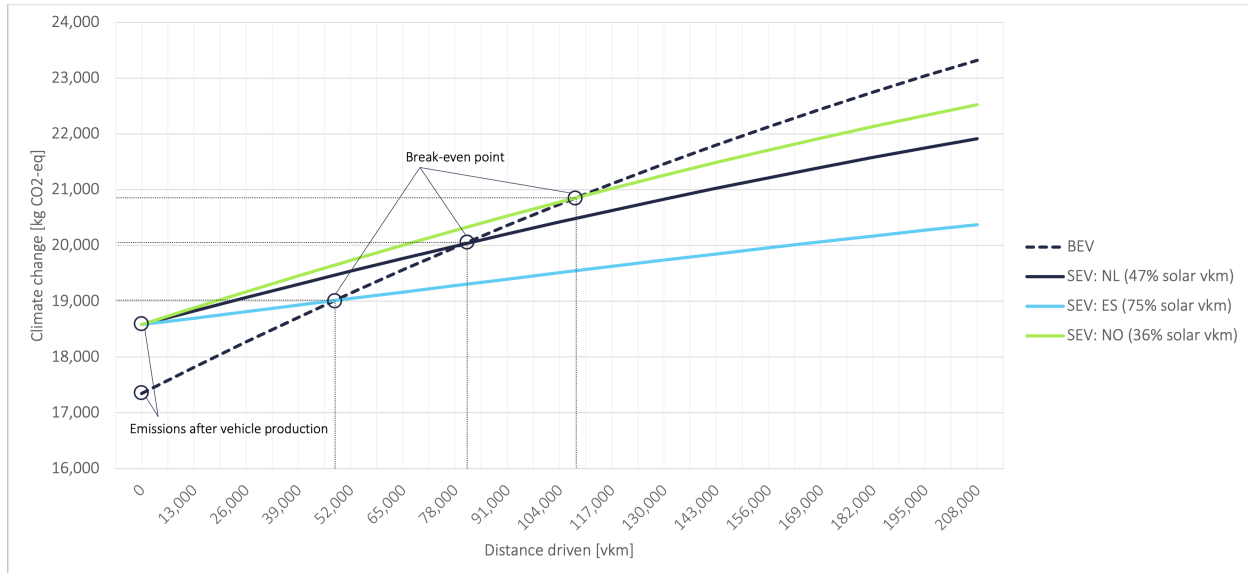


Figure 17: Effects of different annual global horizontal irradiance values on CC impact of the vehicle projected over the distance driven.

### 4.3.3 Driving behavior

A sensitivity analysis on the effects of the different driving behaviors on the impacts showed that the least CC impacting driving profile is the *150 km weekend* driven by the SEV (Figure 18). To include future improvements of the electricity grid related to the decrease in carbon intensity, it was assumed that the grid caused 0.01 kg CO<sub>2</sub>-eq/kWh less impacts every 13,000 vkm (one year of driving). After the vehicle production phase and a use-phase of 200,000 vkm with the *150 km weekend* profile the SEV resulted in 20,700 kg CO<sub>2</sub>-eq. It must be noted that this result did not include the end-of-life (CC impacts related to this phase are shown in the earlier Section 4.1). The reason that the *150 km weekend* driving behavior is the least impacting is due to the share of distance driven on solar kilometers. As the *150 km weekend* driving profile was modelled as a 75 km single trip, it was estimated to use 65% of its required energy generated by the VIPV. Thus, this profile required only 35% of its electricity to be charged from the grid.

The other profiles *35.6 km daily*, *50 km weekday* and *400 km weekend* showed 22,500 kg CO<sub>2</sub>-eq, 22.800 kg CO<sub>2</sub>-eq and 23,800 kg CO<sub>2</sub>-eq, respectively, after a distance driven of 200,000 vkm. This difference in results can be explained as the VIPV for the modelled SEV was capable of generating at most 68.6 kWh/day, which relates to a distance of 70 km/day that can be powered by the VIPV. When a driving profile included a driving distance > 70 km at one day, the share of distance driven that was powered by VIPV generated electricity declined. Therewith, the share of electricity required from the grid increased in these cases which increased the CC impacts of the use-phase.

Thus, this sensitivity analysis showed that the CC impacts of the use-phase are influenced by the share of electricity that is charged by the VIPV. To give a summarised overview, the share of electricity charged by the VIPV versus the electricity charged by the grid is shown in Table 16. The most beneficial driving behavior would consist of one that maximises the share of VIPV generated electricity. This requires a driving profile to not exceed

the peak electricity generation of the VIPV and ideally to not drive on days at which the VIPV cannot generate electricity due to e.g. shade.

Table 16: Electricity charge ratio of VIPV-electricity : grid-electricity.

Driving profile	VIPV-electricity	Grid-electricity	CC after 200,000 vkm
35.6 km daily	44%	56%	22,000 kg CO <sub>2</sub> -eq
50 km weekday	41%	59%	22,200 kg CO <sub>2</sub> -eq
150 km weekend	65%	35%	20,700 kg CO <sub>2</sub> -eq
400 km weekend	26%	74%	23,100 kg CO <sub>2</sub> -eq

The graph visualises the break-even points of the different SEV driving behaviors and the BEV (Figure 18). As the BEV had no VIPV all of its required electricity was charged by the EU electricity grid of 2020 which emitted 0.38 kg CO<sub>2</sub>/kWh, which came to a total of 23,500 kg CO<sub>2</sub>-eq (excluding end-of-life impacts). The CC impacts break-even points of the SEV with the BEV occurred at 53,000 vkm for the *150 km weekends*, 79,000 vkm for the *35.6 km daily*, 83,000 vkm for the *50 km weekday* and 147,000 vkm for the *400 km weekends*, respectively.

It must be noted that these results do not include the time it would take for the different driving profiles until they would reach the distance driven of 200,000 vkm. The *35.6 km daily* and *50 km weekdays* driving profile both come to an annual distance driven of 13,000 vkm per year (the base assumption of this study). This means that they end up driving 200,000 vkm at the same point in time in their operation phase: 15.4 years. While for the *150 km weekends* (7,800 vkm/yr) and *400 km weekends* (20,800 vkm/yr), the 200,000 vkm was reached after an operation of 25.6 years and 9.6 years, respectively. Thus, the *400 km weekends* driving profile did not only result in more CC impacts it also reached this point much earlier than the more sparingly *150 km weekends* profile.

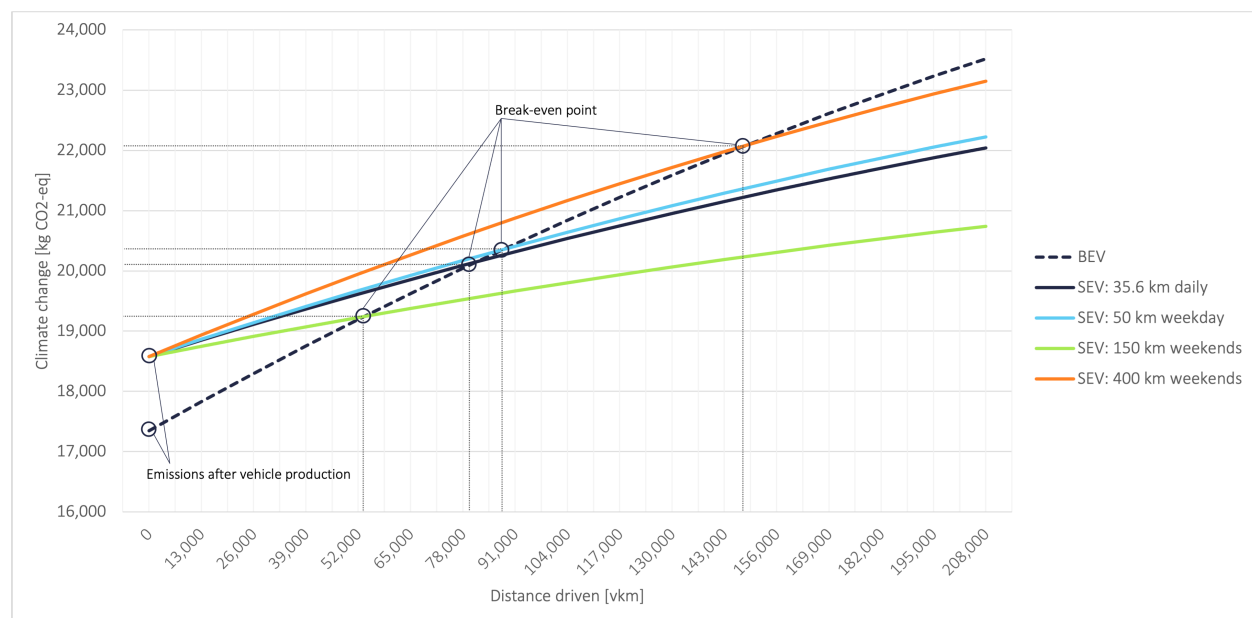


Figure 18: Effects of different driving behavior profiles on CC impact of the vehicle projected over years of use. The EU electricity mix of 2020 of the ecoinvent v3.8 was used for the use-phase of the vehicles.



# DISCUSSION

Pre-development stage of the implementation of VIPV in consumer ready EVs. These are five solar electric vehicles that have been developed to take part in a competition to drive 3021km at the World Solar Challenge in Australia.

Source: Solar Team Eindhoven (2022)

## 5 Discussion

### 5.1 Reiteration of the research problem and results

This research aimed to investigate the differences in environmental impacts between an SEV with a VIPV system and a BEV with a regular exterior. It is important to stress again that the research was specifically aimed to assess the environmental impacts of the vehicles and therefore did not include other social or economic factors that are important indicators of the complete sustainable performance of an SEV. In order to have a reduced environmental impact compared to BEVs, the VIPV system must be able to generate a significant amount of electricity to outweigh the environmental impacts that are caused by the production of this VIPV system. This study showed less CC impacts for driving an SEV for a full lifetime of 200,000 vkm compared to the BEV, while it showed increased CC impacts for the production phase of an SEV compared to a BEV with regular exterior (with similar vehicle characteristics).

As became clear, the lower environmental impacts of the full life cycle of an SEV were due to the decrease in required grid-electricity in its use-phase compared to the required grid-electricity for a BEV. As the investigated SEV could charge partly via its VIPV system without plugging into the electricity-grid, it was able to decrease total lifetime impacts of the SEV by 10% compared to the modelled BEV, however, results remain highly case specific. Further reductions of environmental impacts of the use-phase could be achieved by further increasing vehicle efficiency, however, as was shown, increasing vehicle efficiency by the use of impacting materials (carbon fibre) do increase vehicle production impacts. Thus, careful material selection in the vehicle design phase is important to limit vehicle production impacts. Another improvement could be achieved by limiting VIPV production impacts. Results showed that one of the main contributors to VIPV production impacts came from electricity use in the production of PV-cells. Less electricity demanding PV-cells such as recycled cells could enable reductions of VIPV production impacts.

Although this study showed decreased impacts for the SEV compared to the BEV, it is important to note that results are highly case specific. The scenario LCA and sensitivity analysis have shown cases in which the CC impacts are highly dependent on factors such as CC mitigation scenarios, vehicle efficiency, GHI and driving behavior. High vehicle efficiency, high GHI values and optimal driving behavior cause the lowest CC impacts in the use-phase of an SEV. Differences in CC impacts between the SEV and BEV become smaller in the more ambitious CC scenario. In the most ambitious scenario (RCP 1.9) the SEV shows slightly decreased impacts compared to the BEV with regular exterior (Figure 15). However, it becomes arguable whether the use of SEVs is still environmentally more beneficial than BEVs in a future where the electricity grid will increasingly become dependent on renewable energy sources.

### 5.2 Interpretation of results

When contextualising the findings of this study with previous LCA research on BEVs and VIPV, there were some results specifically interesting or different. These findings are discussed below:

First, it was expected that the VIPV manufacturing phase would contribute to a significant share of the impacts from the VIPV production, whereas the production of the VIPV requires energy intensive manufacturing processes. However, the LCA results showed that the impacts of the manufacturing phase contributed only for 82.0 kg CO<sub>2</sub>-eq. This is a rather small percentage (6%) of the cradle-to-gate VIPV production compared to the material extraction phase that resulted in a CC impact of 1,340 kg CO<sub>2</sub>-eq (90%) (Figure ??). A previous LCA study on VIPV (Kanz et al., 2020) showed that VIPV manufacturing accounted for 1,140 kg CO<sub>2</sub>-eq for a PV area of 4.8 m<sup>2</sup>. This difference can be explained as different data was included in the LCI than in the study of Kanz et al. (2020), and the data on energy use for the VIPV manufacturing might be an underestimation of the real-life

situation which is elaborated on later (Section 5.3). The LCI of Kanz et al. (2020) included the production of PV-cells in their VIPV manufacturing phase, which in this study was part of the LCI of the material extraction phase. When looking at the differences of the total CC impacts of the VIPV production the results are still different (Table 17), however, these might be realistic due to differences in used materials or production processes.

Table 17: Comparison CC impacts of VIPV production

Reference	VIPV size	CC impacts VIPV production
Kanz et al. (2020)	4.8 m <sup>2</sup>	2,283 kg CO <sub>2</sub> -eq
This study	5.0 m <sup>2</sup>	1,480 kg CO <sub>2</sub> -eq

Another interesting finding is that the break-even point between the SEV and BEV occurs after an operation of 79,000 vkm (6.1 years), which could be interpreted as a rather long period whereas the average person owns its vehicle for 4.1 years (CBS, 2017). In that case, the SEV will only start to outperform the BEV during the operation of its second owner according to the result of this study. However, there is an explanation to this study finding which gives a more realistic perspective whenever comparing environmental impacts of an SEV with those of a BEV with regular exterior. This study had assumed a highly energy efficient vehicle (9.8 kWh/100 km) for both the SEV and BEV compared to other existing studies. Other BEV LCA studies assumed an energy efficiency of 19 kWh/100 km (Girardi et al., 2015), 21.6 kWh/100 km (Koroma et al., 2022) and 23.8 (Held & Schücking, 2019) for vehicles with a quite similar weight to the vehicles in this study (Table 18). The choice for the 9.8 kWh/100 km was made as the SEV of study has this efficiency performance in real-life. For a fair comparison, it was chosen to model the BEV with the same energy efficiency. Although in fact, most BEVs on the current market have a much lower energy efficiency which is more close to the ones in the previous BEV LCA studies. As we have seen in the sensitivity analysis, energy efficiency highly impacts the CC impacts of the vehicles (Figure 16). To conclude, this study presents a fair comparison of an SEV and BEV with similar vehicle characteristics. While in reality the highly efficient SEV might outperform an established BEV more early than 79,000 vkm (6.1 years of operation) in terms of environmental impacts because as the SEV is more efficient than established BEVs.

The assumed energy efficiency in this study directly explains the differences of the use-phase impacts with previous study results on BEVs. As was seen in the results of the characterisation step, the CC impacts of the use-phase of the SEV were lower than the BEV. Even though the BEV resulted in higher impacts in its use-phase, it in fact scores rather low compared to other BEV LCA studies. In this study, the use-phase of the BEV accounted for 8,510 kg CO<sub>2</sub>-eq. While another LCA study on BEVs by Burchart-Korol et al. (2020) shows a use-phase impact of 17,868 kg CO<sub>2</sub>-eq for operation in the EU (Table 18). This is slightly more than twice the result of the current study. This is once again due to the vehicle efficiency, as the referred study assumed a vehicle efficiency of 19.9 kWh/100 km (Burchart-Korol et al., 2020) which is a factor 2 more than the assumed 9.8 kWh/100 km in this study. Thus, this clarifies the almost halved CC impacts in the use-phase of the modelled BEV in this study. For the SEV, use-phase CC impacts were even less whereas 46% can be driven on VIPV-electricity and therefore allowed for a 54% reduction in kWh required from the grid. This emphasizes the importance of energy efficiency embedded in the design of an SEV.

The last interesting result relates to the CC impacts of the production of vehicle components that showed higher impacts in this study compared to previous studies on BEVs. In the study of Koroma et al. (2022) the cradle-to-gate production of vehicle components resulted in 11,300 kg CO<sub>2</sub>-eq (Table 18). While in this study, the production of vehicle components resulted in 17,100 kg CO<sub>2</sub>-eq. This makes the impacts of the full life cycle of the studied SEV higher than the impacts of the cradle-to-gate life cycle of the studied SEV (25,100 kg CO<sub>2</sub>-eq) and BEV (27,800 kg CO<sub>2</sub>-eq) were higher in this study than others (Table 18). These higher impacts in production

were partly caused by the use of additional materials as carbon fibre, titanium and aluminium that contribute that were implemented to increase vehicle efficiency. Another reason why the impacts of vehicle component production were higher in this study could be due to the LCI data on vehicle component production, which was largely based on a generic ecoinvent v3.8 process of vehicle glider production. This data is more outdated than the data that was used by Koroma et al. (2022) and therefore might be the cause of differences in impacts of the vehicle component production. When replacing the CC impacts of this study with the results of other studies, which shown around 6,200 kg CO<sub>2</sub>-eq to 11,500 kg CO<sub>2</sub>-eq less CC impacts in vehicle component production (Table 18). The total impacts of the SEV and BEV in this study would come to a total of roughly 16,200 kg CO<sub>2</sub>-eq and 18,900 kg CO<sub>2</sub>-eq, respectively. This shows that modelling decisions on vehicle component production influences the total environmental impacts of the vehicles under study. However, in this particular study, the differences in vehicle use-phase and exterior production give more important indications on the environmental differences between SEVs and BEVs than the absolute environmental impacts of vehicle component production, whereas the modelling of vehicle components for both vehicles was done in the same way.

Table 18: Comparison of SEV and BEV study results with previous LCA studies on BEVs.

References	Vehicle type	Functional unit	Vehicle weight	Vehicle efficiency	CC vehicle production	CC use-phase	CC full vehicle life cycle
Unit		[vkm over lifetime]	[kg]	[kWh/100 km]	[kg CO <sub>2</sub> -eq]	[kg CO <sub>2</sub> -eq/lifetime]	[kg CO <sub>2</sub> -eq/functional unit]
Girardi et al. (2015)	BEV (2013)	150,000	1,479	19	-	~ 16,050	23,265
Girardi et al. (2015)	BEV (2030)	150,000	1,479	19	-	~ 14,500	22,333
Koroma et al. (2022)	BEV	160,000	1,577	21.6	11,300	-	26,500
Held and Schücking (2019)	EV minivan	200,000*	1,700	23.8	~ 7,000	-	23,800
Held and Schücking (2019)	EV compact car	200,000*	1,550	19.0	~ 6,000	-	23,000
Burchart-Korol et al. (2020)	BEV	200,000**	-	19.9	-	17,868	-
This study (2022)	SEV	200,000	1,660	9.8	16,200	4,524	24,900
This study (2022)	BEV	200,000	1,660	9.8	16,200	8,512	28,100

\* Original functional unit of study was 1 vkm over full lifetime. \*\* Original functional unit of study was 100 vkm over full lifetime. These values have been converted to create comparable results.

### 5.3 Limitations

First, the major challenge of this study was to collect empirical data of an emerging technology. The EV sector is constantly developing new technologies and specifically the VIPV technology itself is so novel that production processes and product performance were changing during the conduction of this study. Therefore, data collection of the VIPV system has served some complexities. Ecoinvent served as a database for secondary data, however, the production of PV-cells from ecoinvent is based on production in 2005 and therefore rather outdated. In addition, the early development phase of the VIPV system caused data to be of limited availability. Assumptions had to be made on the amount of required energy and materials for the manufacturing process of VIPV. Site visits helped to make more accurate assumptions, however, at the moment this study was performed, the entire process of production and manufacturing was not yet at its mature state. Thus, reiterations to collect more data would increase the viability of the LCA results.

Second, assumptions on the manufacturing and end-of-life of the VIPV system cause uncertainties in the results. This was due to the fact that the manufacturing of the VIPV-system was still in its early development phase during this study. In addition, within this phase only a few VIPV products were being manufactured and therefore the energy usage of this process was not representing a more mature and up-scaled phase in which multiple products would be manufactured in a single production sequence. Therefore, it was chosen to collect the data on manufacturing energy use from literature (Krebs-Moberg et al., 2021). However, the manufacturing process data of that specific study represents the manufacturing of general PV-panels that were not specifically suited to be applied as VIPV. The manufacturing of VIPV requires lamination and curving processes that probably demand more electricity than generic PV-panels. Thus, the used data might be an underestimation of the realistic manufacturing energy required for VIPV manufacturing. In addition, estimations have been made on the end-of-life of the VIPV system and the regular exterior which might also not be a fully accurate representation of the realistic PV-recycling and treatment.

Third, the LCA research methodology has some general limitations. A generic LCA is more a steady-state analysis rather than a dynamic approach (Guinée, 2001). It is tried to incorporate more prospective elements in this study via performing different scenario LCAs, however, the scenario LCA on the full vehicle lifetime depicts the full life cycle as if it were operated within one year. It still showed how the CC impacts of production and operation of SEVs generally are being influenced by changes in CC mitigation scenarios. However, within that analysis it did not fully show the results of how the use-phase would be impacted by the CC mitigation scenarios.

A generic drawback of the LCA research methodology is that it solely assesses environmental aspects of products, without assessing their economic or social impacts (Guinée, 2001). This causes this research to not be able to capture benefits or drawbacks in economic and social impacts. A drawback in social impacts that was not able to be measured might occur for the MD and FD impact categories. As became clear in the results, the MD impact category is a category in which the SEV performs equally to the BEV. In reality, the issues related to MD might not only cause environmental constraints but also economic and social issues. As is addressed by other researchers, renewable energy technologies require an extensive amount of rare earth materials. Which can impact society in other dimensions than can be expressed by environmental impact results. The availability of rare earth materials is not defined within this LCA research, however, it might be the case that the demand for rare earth materials for wide scale application of VIPV systems is so high that the extraction processes to obtain these materials cannot be operated safely within planetary boundaries. While this is an example of an unmeasured drawback in this study, there might also be unmeasured social advantages of SEVs. As a potential social advantage might be that the electricity generation of the VIPV system enables 'grid in-dependency' of the driver. An SEV can allow a driver to drive places where BEV infrastructure is not developed to a high density in charging poles. In fact, most countries do not enable a high density of BEV charging poles or simply lack to provide a user-friendly operation of BEVs, which holds back the adoption rate of BEVs. In these areas, the use of an SEV might act as a

solution to overcome BEV adoption barriers. In these cases, the adoption of an SEV can become more attractive than adopting a BEV without VIPV. This demonstrates that there can be more social advantages to adopt an SEV above an BEV apart from its environmental impacts.

## 6 Conclusion

The aim of this study was to assess the environmental impacts of an SEV compared to the impacts of a BEV with regular exterior. This study mainly dived into CC impacts through assessing the full vehicle life cycle with a functional unit of 200,000 vkm and 1 vkm. In addition, it assessed the effects of CC mitigation scenarios, vehicle efficiency, GHI and driving behavior on CC impacts of SEVs. This section draws conclusions on all the addressed factors.

### *Total impact results*

- The production phase of the SEV with 5 m<sup>2</sup> causes more environmental impacts than a BEV in the impact categories CC, AC, ER, FD and MD. For the CC impact specifically, the production of an SEV causes 1,230 kg CO<sub>2</sub> more impacts than the production of a BEV (Table 20).
- The functional unit of driving a distance of 200,000 vkm and 1 vkm results in less environmental impacts for the SEV in the impact categories CC, AC, ER and FD. The MD impacts of both vehicles resulted in roughly the same value (Table 19).

Table 19: Environmental impacts for the cradle-to-grave life cycle of the SEV and BEV per 1 vkm.

Impact category	CC	AC	ER	FD	MD
Unit	kg CO <sub>2</sub> -eq	kg SO <sub>2</sub> -eq	MJ	kg oil-eq	kg Fe-eq
Total SEV	1.26E-01	9.76E-04	1.46	3.76E-02	1.16E-01
Total BEV	1.39E-01	1.03E-03	1.61	4.15E-02	1.16E-01

### *Effect of CC mitigation scenarios on CC impacts*

It can be concluded that the addition of a VIPV to a BEV can potentially limit CC impacts in the use-phase compared to a BEV without VIPV, however, when the SEV is charged by an electricity-grid that has a low carbon-intensity, the SEV might only marginally outperform BEVs with a regular exterior (Table 20). In a future scenario with ambitious CC measures, the electricity grid will be powered by a higher share of renewable energy sources. In that case, the CC impacts of charging a BEV will become smaller and therefore the difference in use-phase CC impacts between SEVs and BEVs declines. This means that the full life cycle CC impacts of BEVs would become more equal to the CC impacts of SEVs. In this study, the energy intensive production process of the VIPV system caused 1,230 kg CO<sub>2</sub>-eq more CC impacts than the production of a regular vehicle exterior. Thus, the potential degree of CC impact reductions by substituting a BEV with an SEV is the highest in areas where the electricity grid is not mainly depending on renewable energy sources already. To conclude, substituting BEVs with SEVs to reduce CC impacts would make the most sense in areas where the electricity-grid has a high carbon-intensity.

### *Effect of vehicle efficiency on CC impacts*

Increasing vehicle efficiency seems to effectively decrease CC impacts similar to the effect that VIPV can have on a vehicle and improving vehicle efficiency can potentially even contribute more to use-phase impact savings than substituting a regular exterior by VIPV. Both vehicle efficiency and VIPV decrease the amount of electricity required from the electricity grid, however, the relative decrease in CC impacts that the VIPV can deliver depends on the energy efficiency of the vehicle. This means that the addition of VIPV has a higher benefit when applied to a more efficient vehicle. An improvement in vehicle efficiency has a more continuous influence on decreasing use-phase CC impacts, while the drawback of VIPV is that it can only deliver a certain maximum decrease in CC impacts depending on GHI and on the peak electricity generation per day of the VIPV (Table 20).

### *Effect of GHI on CC impacts*

This study has shown that the use-phase CC impacts of the SEV are influenced by the GHI value in which the vehicle is operated. A higher GHI value increases the share of electricity charged by VIPV and decreases the share of electricity required from the local electricity grid (Table 20). Thus, reductions of use-phase CC impacts can be maximised when an SEV is operated in an area with high GHI values.

### *Effect of driving behavior on CC impacts*

To conclude, driving behavior influences the ratio of VIPV-electricity to grid-electricity that powers the battery off the SEV, where the least CC impacting driving behavior was linked to a high share of VIPV-electricity (Table 20). A driving behavior that includes long driving distances on a single day is likely to require an amount of electricity that exceeds the peak electricity generation of the VIPV. This results in increased CC impacts compared to driving profiles that have more evenly distributed driving distances over each day. At least a certain percentage of the electricity should be powered by the VIPV, otherwise the increased CC impacts from the production of the VIPV compared to a regular vehicle exterior would not be compensated by the VIPV-electricity.

Furthermore, the decrease of environmental impacts from SEVs compared to BEVs does not imply that SEVs have better environmental performance above other modes of transportation (e.g. bikes and public transportation). In that sense, producing more vehicles will always increase impacts on the environment than not producing them at all. In some situations, SEVs could serve as a reasonable alternative to BEVs. Nevertheless, using other, less carbon-intense transportation options to replace BEVs might have a greater potential to decrease environmental impacts from the transportation sector than trying to solve this issue with SEVs. Although SEVs might be shed in a better light than BEVs in this study, it must be stressed the SEV benefits addressed in this study solely concern environmental impacts with a more close focus on CC impacts. Although not studied, factors such as social impacts, economic aspects and material scarcity do form an indispensable part of the complete picture on sustainable performance of SEVs.

As a last conclusion, this study has provided new research findings in the CC impacts of VIPV systems and SEVs. Compared to other studies, it has added value by assessing the CC impacts of SEVs in different cases where the influence of driving behavior, GHI and vehicle efficiency has been assessed. A new insight compared to previous studies is the influence of VIPV on the CC impacts of SEVs with different vehicle efficiencies (kWh/km).

## **6.1 Recommendations**

Recommendations for future SEV research are listed below:

1. Future SEV LCA research could focus on improving the primary LCI data collection of the VIPV manufacturing and recycling. LCI data on VIPV manufacturing energy was mostly collected from generic ecoinvent v3.8 processes of PV-panel manufacturing and previous LCA research on PV-panels. Thus, future studies could focus on a more accurate representation with primary data directly from the VIPV manufacturer. This would increase the viability of results on environmental impacts from VIPV systems. Furthermore, future research could investigate reliable data on vehicle component production to increase reliability of comparison between BEVs with regular exteriors and SEVs with VIPV.
2. Follow-up research could focus on the effects of producing electricity by the use of VIPV compared to regular PV-panels to decrease the electricity demand required from the electricity-grid. As VIPV can decrease the electricity demand that is currently used to charge BEVs, it would be interesting to investigate if the use of VIPV can reduce CC impacts that would otherwise be caused by the electricity-grid and if it would make sense to produce VIPV systems in stead of regular PV-panels.
3. The effect of vehicle efficiency compared to the effect of VIPV on the CC impacts of vehicles could be investigated in further depth. Increasing vehicle efficiency might increase production CC impacts due to

Table 20: Summary of CC impacts results.

	CC impacts SEV [kg CO <sub>2</sub> -eq]	CC impacts BEV [kg CO <sub>2</sub> -eq]	Reduction
Vehicle component production	17,100	17,100	
Exterior production	1,480	248	
Use-phase	4,520	8,510	-47%
End-of-life	1,950	1,980	
Total	25,100	27,800	-10%

CC mitigation scenario	CC VIPV prod. (2050)	Reduction	CC Regular exterior prod. (2050)	Reduction
Base	1,340 kg CO <sub>2</sub> -eq	-9%	230 kg CO <sub>2</sub> -eq	-7%
RCP 2.6	680 kg CO <sub>2</sub> -eq	-54%	170 kg CO <sub>2</sub> -eq	-31%
RCP 1.9	550 kg CO <sub>2</sub> -eq	-63%	150 kg CO <sub>2</sub> -eq	-40%

Vehicle efficiency [kWh/100 km]	Use-phase CC impacts BEV	CC impacts reduction SEV	Reduction CC impacts use-phase
9.8	6,000* kg CO <sub>2</sub> -eq	-2,830 kg CO <sub>2</sub> -eq	-47%
20	12,200 kg CO <sub>2</sub> -eq	-2,830kg CO <sub>2</sub> -eq	-23%
50	30,600 kg CO <sub>2</sub> -eq	-2,830kg CO <sub>2</sub> -eq	-9%

GHI [kWh/m <sup>2</sup> /yr]	Use-phase CC impacts BEV	CC impacts reduction SEV	Reduction CC impacts use-phase
747	6,000* kg CO <sub>2</sub> -eq	-1,790 kg CO <sub>2</sub> -eq	-34%
982		-3,340 kg CO <sub>2</sub> -eq	-44%
1537		-3,950 kg CO <sub>2</sub> -eq	-70%

Driving behavior	Use-phase CC impacts BEV	CC impacts reduction SEV	Reduction CC impacts use-phase
400 km/weekend	6,100* kg CO <sub>2</sub> -eq	-1,600 kg CO <sub>2</sub> -eq	-26%
50 km/weekday		-2,500 kg CO <sub>2</sub> -eq	-41%
35.6 km/day		-2,700 kg CO <sub>2</sub> -eq	-44%
150 km/weekend		-4,000 kg CO <sub>2</sub> -eq	-65%

\* Use-phase CC impacts results were lower in the sensitivity analyses than in the steady state reference case LCA as the sensitivity analyses were modelled with CC impact reductions in the grid electricity with -0.01 kg CO<sub>2</sub>-eq/yr.

the use of carbon-intensive materials, however, it would be interesting to research how this relates to the CC impacts of the production of a VIPV system and which factor has the most benefits.

- Continuation of prospective LCA research would increase understanding of future environmental impacts of SEVs. This study is one of the few to assess the impacts of SEVs and VIPV systems. More research on the environmental impacts of SEVs is required to create a viable picture on the environmental performance of this developing technology. In addition, it remains important to include prospective LCAs as the technology of VIPV is still in its early development phase, which will likely develop fast in the coming decade. Changes will occur in production processes, required materials and manufacturing energy which affects the results of the LCA. Development towards a more prospective form of LCA which continuously monitors changes in the technology would help to increase viable knowledge on environmental impacts of SEVs and its VIPV systems.

5. Assessments of material scarcity and supply chain issues that are related to the production of a VIPV system are important to understand whether global production of VIPV can be operated safely within planetary boundaries. Besides increasing scientific knowledge in this area, it is inherently important to create awareness within the automotive industry of the environmental consequences of the global implementation of VIPV systems.
6. Future research in the social impacts, economic impacts and material scarcity of SEVs is required to create an understanding of a more complete picture of the sustainable performance of SEVs. This study provided an understanding of the environmental impacts, however, it does not fully cover all sustainability aspects of the novel VIPV technology. This study serves as a first step to identify environmental impacts and areas of improvement in VIPV and sets a stepping stone for further research in other sustainability aspects of SEVs and VIPV systems.
7. Furthermore, follow-up research could compare the CC-impacts of the production and use of SEVs compared to the CC-impacts of the electricity grid. As the production of VIPV-electricity can relieve some of the tension on the electricity grid. Whenever SEVs would be implemented in large scale volumes, the demand for grid electricity reduces. It could be researched whether total CC impacts can be saved by the global production and use of VIPV systems on vehicles.
8. Lastly, SEV LCAs should also be compared to other modes of transportation in order to understand in what way SEVs can contribute to a more environmentally friendly transportation sector. This will help researchers understand in which cases SEVs could contribute to the transportation sector without actually producing more environmental impacts within the transportation sector than were already existing.

## References

- A2MAC1. (2022). *Innovative benchmarking platform*. Retrieved August 9, 2022, from <https://www.a2mac1.com/>
- Abdelhamid, M. (2014). *A comprehensive assessment methodology based on life cycle analysis for on-board photovoltaic solar modules in vehicles hybrid concentrated solar power (csp)/ photovoltaic system (pv) with thermal energy storage system view project*. [http://tigerprints.clemson.edu/all\\_dissertations](http://tigerprints.clemson.edu/all_dissertations)
- Accardo, A., Dotelli, G., Musa, M. L., & Spessa, E. (2021). Life cycle assessment of an nmc battery for application to electric light-duty commercial vehicles and comparison with a sodium-nickel-chloride battery. *Applied Sciences (Switzerland)*, *11*, 1–32. <https://doi.org/10.3390/app11031160>
- Alghoul, M., Hammadi, F., Amin, N., & Asim, N. (2018). The role of existing infrastructure of fuel stations in deploying solar charging systems, electric vehicles and solar energy: A preliminary analysis. *Technological forecasting social change*, *137*, 317–326. <https://doi.org/10.1016/j.techfore.2018.06.040>
- Auke Hoekstra, A., & Steinbuch, M. (2020). *Comparing the lifetime green house gas emissions of electric cars with the emissions of cars using gasoline or diesel*.
- Automotiveworld. (2022). Retrieved August 9, 2022, from <https://www.automotiveworld.com/articles/driving-on-sunshine-ev-charging-goes-green/>
- Bhatti, A. R., Salam, Z., Aziz, M. J. B. A., & Yee, K. P. (2016). A critical review of electric vehicle charging using solar photovoltaic: A critical review of pv-ev charging. *International journal of energy research*, *40*(4), 439–461. <https://doi.org/10.1002/er.3472>
- Birnie, D. P. (2009). Solar-to-vehicle (s2v) systems for powering commuters of the future. *Journal of power sources*, *186*(2), 539–542. <https://doi.org/10.1016/j.jpowsour.2008.09.118>
- Birnie, D. P. (2016). Analysis of energy capture by vehicle solar roofs in conjunction with workplace plug-in charging. *Solar energy*, *125*, 219–226. <https://doi.org/10.1016/j.solener.2015.12.014>
- BMW Group. (2020). *Environmental report bmw ix3* (tech. rep.). [https://www.bmwgroup.com/content/dam/grpw/websites/bmwgroup.com/responsibility/downloads/en/2016/Environmental-report\\_BMW-i3.pdf](https://www.bmwgroup.com/content/dam/grpw/websites/bmwgroup.com/responsibility/downloads/en/2016/Environmental-report_BMW-i3.pdf)
- Bolin, L. (2020). Life cycle assessment: Carbon footprint of polestar 2. Retrieved April 4, 2022, from <https://www.polestar.com/dato-assets/11286/1600176185-20200915polestarlcafinala.pdf>
- Burchart-Korol, D., Jursova, S., Folega, P., & Pustejovska, P. (2020). Life cycle impact assessment of electric vehicle battery charging in european union countries. *Journal of cleaner production*, *257*, 120476.
- CBS. (2017). *Nederlanders en hun auto* (tech. rep.). <https://www.cbs.nl/nl-nl/achtergrond/2017/08/nederlanders-en-hun-auto>
- CBS. (2020). *Hoeveel rijden personenauto's?* Retrieved May 10, 2022, from <https://www.cbs.nl/nl-nl/visualisaties/verkeer-en-vervoer/verkeer/verkeersprestaties-personenautos#:~:text=In%5C%20coronajaar%5C%202020%5C%20legden%5C%20alle,10%5C%2C5%5C%20duizend%5C%20in%5C%202020.>
- Chertow, M., Clini, C., Musu, I., & Gullino, M. (2008). Industrial ecology in a developing context. *Sustainable Development and Environmental Management*. [https://doi.org/10.1007/978-1-4020-8229-0\\_24](https://doi.org/10.1007/978-1-4020-8229-0_24)
- European Commission. (2010). Institute for environment and sustainability: International reference life cycle data system (ilcd) handbook - general guide for life cycle assessment - detailed guidance [First edition March 2010. EUR 24708 EN.].
- European Commission. (2019). The european green deal. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%5C%3A2019%5C%3A640%5C%3AFIN>
- Ghose, D., Pradhan, S., Tamuli, P., & Shabbiruddin. (2019). Optimal material for solar electric vehicle application using an integrated fuzzy-copras model. *Energy sources. Part A, Recovery, utilization, and environmental effects*, 1–20. <https://doi.org/10.1080/15567036.2019.1668879>

- Girardi, P., Gargiulo, A., & Brambilla, P. C. (2015). A comparative lca of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: The italian case study. *The international journal of life cycle assessment*, 20(8), 1127–1142. <https://doi.org/10.1007/s11367-015-0903-x>
- Guinée, J. (2001). Handbook on life cycle assessment — operational guide to the iso standards. *The international journal of life cycle assessment*, 6(5), 255–255.
- Hachicha, A. A., Al-Sawafta, I., & Said, Z. (2019). Impact of dust on the performance of solar photovoltaic (pv) systems under united arab emirates weather conditions. *Renewable energy*, 141, 287–297. <https://doi.org/10.1016/j.renene.2019.04.004>
- Hawkins, T. R., Gausen, O. M., & Strømman, A. H. (2012). *Environmental impacts of hybrid and electric vehicles-a review*.
- Hawkins, T. R., Singh, B., Majeau-Bettez, G., & Strømman, A. H. (2013). Comparative environmental life cycle assessment of conventional and electric vehicles. *Journal of industrial ecology*, 17(1), 53–64. <https://doi.org/10.1111/j.1530-9290.2012.00532.x>
- Held, M., & Schücking, M. (2019). Utilization effects on battery electric vehicle life-cycle assessment: A case-driven analysis of two commercial mobility applications. *Transportation Research Part D: Transport and Environment*, 75, 87–105. <https://doi.org/10.1016/j.trd.2019.08.005>
- Hyundai. (2022). Retrieved August 9, 2022, from <https://www.hyundai.com/nl/modellen/IONIQ-5b/features.html#>
- IEA. (2022). *Transport* (tech. rep.). Paris. <https://www.iea.org/reports/transport>
- IPCC. (2022). Climate change 2022: Impacts, adaptation, and vulnerability [Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change]. <https://doi.org/10.1017/9781009157926>
- ISO. (2006). *Environmental management — life cycle assessment — requirements and guidelines* (Standard ISO/TC 207/SC 5). International Organization for Standardization. Geneva, CH. <https://www.iso.org/standard/38498.html>
- Kanz, O., Reinders, A., May, J., & Ding, K. (2020). Environmental impacts of integrated photovoltaic modules in light utility electric vehicles. *Energies*, 13. <https://doi.org/10.3390/en13195120>
- Khan, S., Ahmad, A., Ahmad, F., Shemami, M. S., Alam, M. S., & Khateeb, S. (2018). A comprehensive review on solar powered electric vehicle charging system. *Smart Science*, 6(1), 54–79. <https://doi.org/10.1080/23080477.2017.1419054>
- Koroma, M. S., Costa, D., Philippot, M., Cardellini, G., Hosen, M. S., Coosemans, T., & Messagie, M. (2022). Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management. *Science of The Total Environment*, 831, 154859. <https://doi.org/10.1016/j.scitotenv.2022.154859>
- Krebs-Moberg, M., Pitz, M., Dorsette, T. L., & Gheewala, S. H. (2021). Third generation of photovoltaic panels: A life cycle assessment. *Renewable energy*, 164, 556–565.
- Mahmud, M. A. P., Huda, N., Farjana, S. H., & Lang, C. (2019). Comparative life cycle environmental impact analysis of lithium-ion (liio) and nickel-metal hydride (nimh) batteries. *Batteries*, 5. <https://doi.org/10.3390/batteries5010022>
- Meide, M., Harpprecht, C., Northey, S., Yang, Y., & Steubing, B. (2022). Effects of the energy transition on environmental impacts of cobalt supply: A prospective life cycle assessment study on future supply of cobalt. *Journal of Industrial Ecology*. <https://doi.org/10.1111/JIEC.13258>
- Mutel, C. (2017). Brightway: An open source framework for life cycle assessment. *Journal of Open Source Software*, 2(12), 236. <https://doi.org/10.21105/joss.00236>
- N, H., Hampannavar, S., B, D., & M, S. (2021). Analysis of microgrid integrated photovoltaic (pv) powered electric vehicle charging stations (evcs) under different solar irradiation conditions in india: A way towards sustainable development and growth. *Energy reports*, 7, 8534–8547.

- Nordelof, A. (2018). A scalable life cycle inventory of an automotive power electronic inverter unit—part ii: Manufacturing processes. *The international journal of life cycle assessment*, 24(4), 694–711.
- Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M., & Van Mierlo, J. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The international journal of life cycle assessment*, 19(11), 1866–1890.
- Novoa, L., & Brouwer, J. (2018). Dynamics of an integrated solar photovoltaic and battery storage nanogrid for electric vehicle charging. *Journal of power sources*, 399(100), 166–178.
- O’Neill, B., Kriegler, E., Riahi, K., Ebi, K., Hallegatte, S., Carter, T., Mathur, R., van Vuuren, D., & Sciences, E. (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic change*, 122(3), 387–400.
- Pesonen, H. .-, Ekvall, T., Fleischer, G., Huppes, G., Jahn, C., Klos, Z. S., Rebitzer, G., Sonnemann, G. W., Tintinelli, A., Weidema, B. P., & Wenzel, H. (2000). Framework for scenario development in lca. *The international journal of life cycle assessment*, 5(1), 21–21.
- Polestar. (2020). *Life cycle assessment - carbon footprint of polestar 2* (tech. rep.). Göteborg, SE. <https://www.polestar.com/dato-assets/11286/1600176185-20200915polestarlcafinala.pdf>
- Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O’Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., . . . Tavoni, M. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global environmental change*, 42(January 2017), 153–168.
- Ritchie, H., & Roser, M. (2020). Energy [<https://ourworldindata.org/energy>]. *Our World in Data*.
- Sacchi, R., Bauer, C., Cox, B., & Mutel, C. (2022). When, where and how can the electrification of passenger cars reduce greenhouse gas emissions? *Renewable and Sustainable Energy Reviews*, 162, 112475. <https://doi.org/https://doi.org/10.1016/j.rser.2022.112475>
- Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., & Luderer, G. (2022). Prospective environmental impact assesment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renewable and Sustainable Energy Reviews*, 160. <https://doi.org/10.1016/j.rser.2022.112311>
- Sierra Roiguez, A., de Santana, T., MacGill, I., Ekins-Daukes, N., & Reinders, A. (2020). A feasibility study of solar pv-powered electric cars using an interdisciplinary modeling approach for the electricity balance, co2 emissions, and economic aspects: The cases of the netherlands, norway, brazil, and australia. *Progress in photovoltaics*, 28(6), 517–532.
- SolarGis. (2022). Solar resource maps of europe. Retrieved August 4, 2022, from <https://solargis.com/maps-and-gis-data/download/europe>
- Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, C., & Prins, A. (2014). *Integrated assessment of global environmental change with image 3.0. model description and policy applications*. The Hague: PBL Netherlands Environmental Assessment Agency.
- Steubing, B., de Koning, D., Haas, A., & Mutel, C. L. (2020). The activity browser — an open source lca software building on top of the brightway framework. *Software Impacts*, 3, 100012. <https://doi.org/https://doi.org/10.1016/j.simpa.2019.100012>
- Talukdar, B., Deka, B., & Goswami, A. (2021). An approach to reliability modeling and availability analysis of a solar electric vehicle with standby plug [U+2010]in facility. *International Transactions on Electrical Energy Systems*. <https://doi.org/10.1002/2050-7038.13147>
- Temporelli, A., Carvalho, M. L., & Girardi, P. (2020). *Life cycle assessment of electric vehicle batteries: An overview of recent literature*. <https://doi.org/10.3390/en13112864>

- UNFCCC. (1992). *United nations framework convention on climate change* (tech. rep.). Bonn, Germany. [unfccc.int/resource/docs/convkp/conveng.pdf](https://unfccc.int/resource/docs/convkp/conveng.pdf)
- van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G., Kram, T., Krey, V., Lamarque, J., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S., Rose, S., Sciences, E., & Sciences, S. E. (2011). The representative concentration pathways: An overview. *Climatic change*, *109*(1-2), 5–31.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2021). *The ecoinvent database version 3.8* (tech. rep.). Retrieved April 4, 2022, from <http://link.springer.com/10.1007/s11367-016-1087-8>

# Appendices

Table 21: Detailed Life cycle inventory: VIPV system (CONFIDENTIAL).

<b>Output</b>	<b>Mass</b>	<b>Unit</b>	<b>Resource</b>
PV-panel	1	square meter	
Waste plastic	1.69	kg	Vehicle manufacturer
<b>Input</b>			
<i>Product materials</i>			
Photovoltaic cell, single-Si wafer	1	square meter	Vehicle manufacturer
Polysterene foam slab	0.2	kg	Vehicle manufacturer
Glass fibre reinforced plastic	2.2	kg	Vehicle manufacturer
Ethylene vinyl acetate copolymer	1.2	kg	Vehicle manufacturer
Copper cake	0.3	kg	Vehicle manufacturer
PE terephthalate	0.1	kg	Vehicle manufacturer
Solar glass	5	square meter	Vehicle manufacturer
Polyurethane, rigid foam	0.8	kg	Vehicle manufacturer
Polyutherane adhesive	0.17	kg	Vehicle manufacturer
Cable	0.1248	kg	Vehicle manufacturer
<i>Manufacturing</i>			
Corrugated card box	1.09	kg	Ecoinvent
Brazing solder	8.7E-3	kg	Ecoinvent
Heat	4.86	MJ	Vehicle manufacturer
Electricity	4.7	MJ	Author's estimate
Photovoltaic panel factory	4E-6	unit	Author's estimate