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ECOFLEX

D7.2 Life Cycle Assessment Data Provision

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Abstract for dissemination (PU)

The deliverables' main objective is to present collected data relevant for conducting a life cycle assessment of electric vehicles providing flexibility services at different scales. First, the current literature is reviewed to identify research gaps. Based on the identified research gaps, an assessment framework is defined including a novel methodology to evaluate environmental impacts of flexibility services in a micro-, mezzo-, and macro-level use case. Defining the framework and novel methodology is done in order to determine the data requirements for the assessments, presented after the methodology. Finally, an outlook alongside with the next steps are concluding this deliverable. Results of the applied framework will be presented in the next deliverable D7.3 Report on the Sustainability impacts.

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1. Introduction

Electrification of the transport fleet is one strategy to decarbonize the transport sector and thus limit the rise of the global surface temperature to well-below 2°C by many member states of the European Union. While sales of electric vehicle (EV) experienced a steady increase within the last decade, individual passenger EV are parked around 95% of the day [1]. At the same time, one way of decarbonizing the energy sector is to introduce more renewable energy technologies, characterized by high volatility, which hampers reliable integration into national energy supply. Consequently, those two recent trends can benefit from each other's synergies: more EV with continuously growing battery sizes become available in the next years, but remain unused most of their time. Additionally, their electricity demand does not necessarily have to be met immediately, opening the possibility to re-schedule the charging session for example to hours of low electricity prices. Next to this, energy systems are built more on renewable energy sources, requiring storage technologies to overcome their intermittent nature. Consequently, during times when not being used for driving, the batteries in the EV can be used to store unused energy produced by renewable energy technologies. Besides functioning as mobile energy storage, EVs also can help introducing a more flexible electricity demand. Upon arrival at the charging station, most EVs spend most of the time plugged to the charger. Thus, their electricity demand does not need to be matched immediately, opening the possibility to schedule the charge to times when for example more electricity is produced by renewable energy carriers. Within this work, three different charging strategies are applied: uni-directional, bi-directional and smart charging, where bi-directional and smart charging is describing flexibility services. Those strategies could help increasing the renewable energy share in the electricity mix and thus lower its impact on climate change (CC). An open question however remains, whether the CC of the systems considering different charging strategies result in significant changes. Thus, the objective of this first deliverable is to provide a framework that shades light on this discussion from different scales, where final results of the developed framework will be presented in the final deliverable of D7.3 Report on the Sustainability impact.

2. State-of-the-art

Since the entry of the EV in the mass market in the last decade, substantial research effort is dedicated to apply the life cycle assessment (LCA) methodology to EVs in order to understand their environmental impacts [2]. Many studies aim to understand the environmental advantage

of an EV over other drivetrain technologies [2]–[4]. Over the time, those studies enhanced their level of details to increase their reliability and to represent reality as good as possible, by introducing a range-based assessment to include variability in LCA of EVs [5]. Additionally, the LCA studies of EVs are applied in different countries in order to cover the environmental impacts during the use stage [6]. At the same time, many LCA studies on the environmental impacts of the battery are published. The first and most well-known studies containing primary life cycle inventory (LCI) data published are from Zackrisson et al. (2010), Majeau-Bettez et al. (2011) and Ellingsen et al. (2014) [7]–[9]. Until now, those studies are frequently used as a reference for modelling mobile battery storage. Since those studies were published, more and more papers have occurred evaluating different battery chemistries, impact categories, use stage assumptions, system boundaries etc. A comprehensive overview of LCA studies on lithium-ion batteries (LIB) is provided by a review published by Peters et al. (2018), where they analysed 79 different studies and summarized their results [10]. They highlight a great variance in GHG emissions, even though the LCI data originate mostly from the same studies, and found the average GHG emissions for the battery production of various chemistries is 110 kgCO₂eq per kWh storage capacity. More recently, research on LCA of EVs is dedicated to understand the environmental impacts of future electricity mix and different end-of-life management, giving the traction batteries a second life and investigating in new materials in the battery [11]–[13]. All of those studies focus on EVs, or their traction batteries and all studies are conducted from an attributional LCA (ALCA) perspective. Further explanation ALCA and other LCA types is provided in section 3.

Investigation of EVs raises always the question about the interaction with the grid, e.g. how much more electricity will be needed to accommodate the foreseen EV uptake, and which implication does the additional electricity demand have on the power system? More recently, new technologies were introduced to manage EVs and their charging in a more flexible way. One possibility is to schedule the EV charging to hours where for example excess electricity is available due to high production of renewable energy and low energy consumption. This technology is referred to as smart charging. Next to smart charging and standard uni-directional charging, where EVs are plugged and charged immediately, the EVs also can be charged bi-directional. Bi-directional charging would allow EVs to not only be charged with electricity, but also discharge electricity back to a consumer or the national grid. Over the years, a range of new flexibility services considering both uni- and bi-directional charging are explored, for example but not limited to peak shaving, valley filling or grid balancing [14]–[16]. Quantifying

environmental impacts of such flexibility services poses several challenges: first, the proposed solution does not imply additional infrastructure, apart from additional power electronics at charger or electric vehicle level, to allow bi-directional flow [17]. Thus, on a first glance the environmental impacts of such services seems equal to EVs being charged uni-directional. However, when an EV is providing bi-directional charging, e.g. powering a vehicle and feeding back electricity to a location, this is understood as multi-functional process in LCA terminology. In LCA, processes or activities providing two or more services or products are referred to as multi-functional processes. In order to understand the environmental impacts of such multi-functional processes, one way to address the challenge of multi-functional processes is the allocation of environmental impact of the production of the EVs to the two provided services. Another argument to allocate environmental impacts to bi-directional charging of the EV is the potential impact on the battery capacity. The additional charge and discharge behaviour due to bi-directional charging can pose additional stress on the battery and thus can reduce its lifetime. However, a lack of scientific confirmation leaves this research area open for further exploration [17].

Second, modelling the use stage of an EV providing any type of flexibility service requires, due to its complex interaction at the charging point, a more comprehensive modelling of the energy system. Modelling an energy system including EVs providing flexibility services is until now done mostly from a macro-level perspective: Xu et al. (2020) for example study different EV charging strategies, including vehicle-to-grid (V2G), and implied environmental impacts of the EU energy system in 2050. They integrated attributional LCA into an energy system model (ESM) and found, that V2G services in 2050 could reduce GHG emissions by as much as 47% [18]. The environmental impacts of the battery production used in the EVs to provide the V2G service remain unaddressed. Furthermore, the modelling considers only static EV profiles to quantify the bi-directional charging. Another example is provided by Wang et al. (2021): they analyse different aggregation methods of EVs providing flexibility service into an ESM to understand the implications on the environmental impacts [19]. While they take into account electricity stored by the battery of the EVs, a specification on the allocation of the environmental impacts of the battery is absent. Furthermore, Nilges et al. (2024) present EVs as assets to do demand-side management, defined as load-shifting of demand to hours with low electricity prices, in order to understand the consequences on the GHG emissions [20]. However, they do not use LCA to quantify the environmental impacts of the future German energy system integrating EVs. Another study investigates single- and bi-directional charging strategies of EVs and found the

three following flexibility benefits: the bi-directional charging strategy is found to (i) reduce the total charging costs, (ii) improve the utilization rate of renewable energy shares and (iii) reduce carbon emissions [21]. In this study, obtained carbon emissions from another LCA study are monetized by a carbon price and together with the economic costs formulated as a minimization problem in the objective function of the ESM.

Apart from the presented studies, which rather focus on the technical modelling of EVs and their flexibility potential from a macro-perspective, first attempts are made towards identifying environmental impacts of the flexibility services by applying LCA. In their study, Rovelli et al. (2021) coupled consequential LCA (CLCA) with an ESM called EnergyPLAN to understand consequences of EVs use stage [22]. Even though they limit their study to uni-directional charging, they claim that without additional installation of RES capacities, the future electricity demand of EVs might increase the impact on CC by up to 40% compared to their business-as-usual (BAU) scenario. Similarly, Zhao et al. (2022) assesses EVs as stationary storage in the United Kingdom in 2050 and the resulting effects on the environmental impacts [23]. In their study, they present four different future options for EV batteries considering different battery chemistries: a) flexibility services, b) battery swapping, c) reuse and d) stationary battery storage. For flexibility services, they found, compared to 0.165 kgCO₂eq/kWh in 2018, the carbon footprint of the energy system can be reduced to 0.036 kgCO₂eq/kWh in 2050. The study is conducted without making use of an ESM and thus, EVs and their flexibility potential is considered in a static manner, neglecting dynamic behaviour of EV drivers.

Contrary to existing studies evaluating the macro-level perspectives of EVs providing flexibility services, Wohlschlager et al. (2024) published a study that aims on revealing environmental effects of V2G charging in the future German energy systems next to evaluating impact on the battery of those EVs [24]. As starting point, they used the European linear optimization multi-ESM and coupled it with prospective LCA (PLCA) to obtain the hourly grid electricity mix in 2050. The PLCA focuses on revealing the difference in terms of CC impacts between uncoordinated and bi-directional charging of EVs. Additionally, they introduced two levels of assessment: a) the environmental impacts of the complete energy system is calculated and b) the environmental impacts on the technology level, e.g. on the EVs is determined.

As presented, the main focus on existing literature is on revealing the impacts of providing flexibility services by EVs on a national or larger energy system (identified in Table 1 as macro-level), where in some studies the application of LCA is rather limited, e.g. by either due to using secondary data on environmental impacts from other studies or lacking reporting [19], [21]. Studies focusing on conducting a transparent and comprehensive LCA to assess different charging strategies of EVs are available [22], [23]. While Rovelli et al. (2021) is using an ESM coupled with CLCA, they assess uni-directional charging only, neglecting the potential to provide bi-directional charging services. Contrary, Zhao et al. (2022) is assessing environmental impacts of flexibility services of EVs, but lacks coupling it to an ESM [23]. Next to all the studies focusing on the macro-level assessment of flexibility services, Wohlschalger et al. (2024) tackles the implications of flexibility services both on a macro- and micro-level, namely the battery of the EVs [24].

While this is a step forward towards revealing the implications of EVs providing flexibility services, current literature neglects the fact, that different flexibility services might benefit different users and thus cannot necessarily be revealed on a macro-level scale. Currently missing is a comprehensive methodology to assess the environmental impacts of various flexibility services provided at different scales including adjusted scopes to reveal the actual environmental impacts. Thus, this work complements existing literature by proposing a methodology to calculate environmental impacts on three different scales: a) a micro-level scale, presenting a residential household providing peak shaving, b) a mezzo-level scale, describing an industrial site offering grid balancing and c) a macro-level scale (national energy system), increasing the integration of renewable energy sources and their utilization rate. Additionally, the following different type of charging strategies are investigated: the base case describes a setup, where EVs are charged uni-directional with and without an additional stationary battery storage (BESS). The third case study is considering smart charging of EVs with BESS and in the last case study, EVs are allowed to be charged bi-directional. Therefore, the following research questions will be addressed during this work:

- How should different scales be defined to evaluate the environmental impacts of EVs providing flexibility services?
- How would a new methodology look like in order to calculate the environmental impacts of those different scales?

- What are the environmental impacts of different flexibility services applying the new methodology and different scales?

<i>Source</i>	<i>Geographical</i>		<i>Flexibility type</i>	<i>Level</i>	<i>Inclusion EV</i>		<i>ESM</i>	<i>Impact</i>
	<i>scope</i>	<i>Time</i>			<i>battery</i>	<i>LCA type</i>		
[18]	Europe	2050	Uni-& bidirectional	Macro	No	n.a.	PERSEUS-EU model	CC (ReCiPe)
[19]	Germany	2050	V2G	Macro	No	n.a.	Own development	CC (ReCiPe)
[20]	Germany	2050	Demand-side mgmt.	Macro	No	no LCA	Own development	GHG emissions
[21]	China	n.a.	Uni-& bidirectional	Macro	No	no LCA	Own development	n.a.
[22]	Italy	2030	Uni-& bidirectional	Macro	No	CLCA	EnergyPLAN	ILCD 2.0 midpoint
[23]	UK	2050	V2G	Macro	No	n.a.	n.a.	ReCiPe
[24]	Germany	2050	Uni-& bidirectional	Macro-Micro	No	PLCA	ISaR	CC (IPCC 2013 no LT)

Table 1: Summary of main findings from literature on life cycle assessment of EVs providing flexibility services. A more detailed explanation on the LCA type is provided in the following section 3 (EV = electric vehicle, LCA = life cycle assessment, ESM = energy system model, CC = climate change, V2G = vehicle-to-grid, CLCA = consequential LCA, PLCA = prospective LCA, n.a. = not available).

3. Assessment framework

To quantify the environmental impacts related to the flexibility EVs could provide, three different use cases are defined, taking into account different scales and scopes: a) a micro-level use case, b) a mezzo-level use case and c) a macro-level use case (see Figure 1).

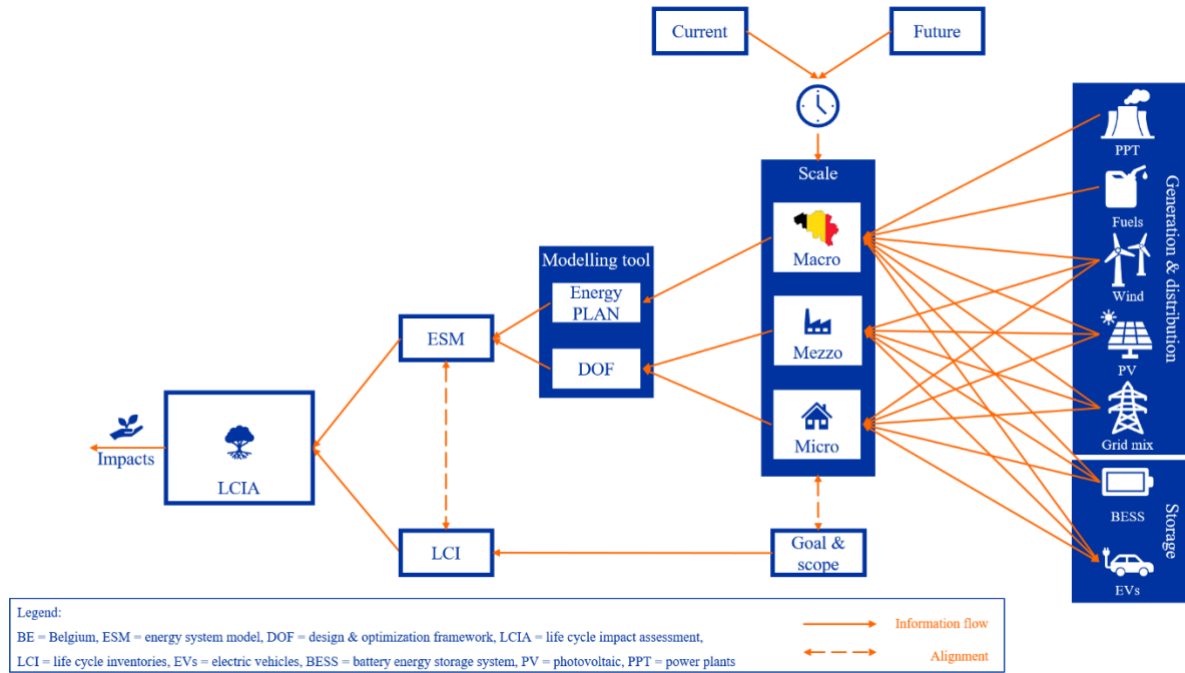


Figure 1: Overview on different use cases to assess the environmental impacts of flexibility provided by EVs on a micro-, mezzo-, and macro-level including the respective environmental system impacts (EV = electric vehicles, PV = photovoltaic, RES = renewable energy sources, BESS = battery energy storage system).

The aim of this study is to conduct three different LCAs for revealing the environmental impacts of EVs providing flexibility services. LCA methodology was chosen as it is a well-recognized method for evaluating environmental impacts of a product or service. In general, two different LCA approaches can be distinguished: the attributional LCA (ALCA) represents a methodology which aims to understand the flow of environmental impacts within a given timeframe. It is a model, where input and output data are assigned to the function of the system [25]. Thus, the ALCA is also described as an accounting methodology. Next to the ALCA, there is the consequential LCA (CLCA). The CLCA is described as methodology which investigates how environmental impacts change due to a change in demand [25]. Another LCA methodology, which is not applied in this study, but presented in section 2 is prospective LCA (PLCA). PLCA aims at evaluating environmental impacts of products or services occurring in the future, for example by considering learning effects during the upscaling of emerging technologies and progress and technological changes of the wider economy, future impacts are

expected to vary [26]. Due to their fundamental difference in functionalities, a direct comparison of environmental impacts assessed by the presented LCA methodologies is neither possible nor the objective of this work.

In the micro-level use case, one EV is charged or discharged at an average Belgian household with a PV installation supported by electricity consumption from the national Belgian electricity mix. At the micro-level, the EV is providing peak shaving and valley filling service with the objective to increase the self-consumption of PV generated electricity. As providing the services is technologically already feasible, the year 2023 is selected as time scope. In particular, this means that some electricity normally consumed from the national Belgian electricity mix is replaced with electricity supplied by the EV. As one potential consequence, at the micro-level, the consumption of national Belgian electricity mix could be reduced and instead more self-generated PV electricity would be consumed, stored in the battery of the EV. Furthermore, different level of flexibility services are considered: standard uni-directional charging, smart and bi-directional charging. Those different flexibility services can result in different system layout: as a starting point, the standard uni-directional charging with no BESS installation is modelled. In the second flexibility service, the standard uni-directional charging is supported by a BESS. The third flexibility service represents a case where the EV is charged in a smart way including a BESS and the fourth flexibility service foresees bi-directional charging without a BESS. Thus, environmental impacts of the systems where no BESS is installed, should theoretically be lower compared to the systems where BESS are installed. Furthermore, different system designs for the same household electricity demand is expected due to the different charging strategies. Additionally, providing the bi-directional charging strategy at the micro-level does not come for free: an EV is required, in particular its battery to provide the service next to its main purpose to power the vehicle. This multi-functional process presents a challenge in LCA, as those environmental impacts of this process have to be divided between the two services, namely supplying electricity for driving and for energy storage purposes. The ISO 14040 presents solutions to address the problem of environmental impacts of multi-functional processes [27], amongst them economic and physical allocation, substitution or system expansion. Applying a physical allocation based on discharged electricity allows to account for the environmental burden of manufacturing the battery in an EV when modelling the bi-directional charging strategy for EVs at the micro-level. Hence, to identify whether the environmental impacts of one charging strategy outstands the others, each

charging strategy is evaluated considering the environmental impact of the entire system. Therefore, a functional unit of one kWh of generated electricity is chosen.

The mezzo-level use case represents an industrial site in Belgium, where the electricity supply is, apart from PV installations and national Belgian electricity mix, supported by a BESS. Similar to the micro-level use case, the time scope in the mezzo-level use case refers to 2023. At the mezzo-level, the same four charging strategies are investigated, but now at a larger scale with the objective to reveal the importance of scale. Again, the four different charging strategies are: first, standard uni-directional charging without BESS; second, standard uni-directional charging with BESS; third, smart charging with BESS and fourth, bi-directional charging without BESS. Instead of modelling a single EV, a fleet of EVs is considered at the industrial site. Similar to the micro-level use case, the EV fleet providing flexibility services does not come without an environmental burden and thus, the same allocation is used to determine the environmental burden of manufacturing the EV fleet batteries as in the micro-level use case. Furthermore, those different charging strategies will result in different system layouts and thus, turn out in different environmental impacts. Again, the same metrics are used to evaluate the environmental impacts of the mezzo-level use case: a system assessment is applied, where the functional unit is set to be one kWh of generated electricity.

An ALCA is used to evaluate the micro- and mezzo-level use case. As the objective of the micro- and mezzo-level use case is to study the environmental impacts of the system at smaller scales considering different charging strategies rather than identifying changes in the system, choosing an ALCA is justified. Consequently, results at the micro- and mezzo-level are calculated for uni-, bi-directional and smart charging with different system layouts. A cradle-to-gate approach comprising raw material extraction, component manufacturing, installation and use is selected. Multifunctional processes are modelled using physical allocation. For evaluating uncertainty of the background database, a Monte-Carlo analysis is conducted.

In the macro-level use case, the scope is the entire Belgian electricity system, where a share of the Belgian vehicles is assumed to be electric and thus able to provide flexibility services. As such a system is not yet in place, the macro-level use case is assessing a future system in 2050. On the macro-level, the benefits of providing flexibility services reveals twofold: first, the provided flexibility will help balancing the grid and thus increase the utilization factor of installed capacity and second, it will help the electricity system to accommodate more renewable energy sources (RES). Those two implications are expected to result in a decrease

of the environmental impacts per kWh of the national Belgian electricity grid mix. Similar to the previous use cases, the environmental burdens of providing the flexibility service are included by allocating the impact of battery manufacturing according to the discharged electricity for providing bi-directional charging services. The functional unit in the macro-level use case is one kWh of electricity produced in 2050.

Due to the three different scopes chosen to assess the various charging strategies, different LCA methodologies are conducted: a CLCA is applied to reveal the environmental impacts of the macro-level use case in order to understand the changes in the energy system that is caused by providing such services. For comparison reasons, a CLCA is evaluating the environmental impacts of an energy system with smart and uni-directional charging of EVs and a system where the EVs are charged uni-directionally. The functional unit in the macro-level use case is 1 kilowatt hour (kWh) of electricity delivered by the Belgian energy system in 2050. A cradle-to-gate approach comprising raw material extraction, component manufacturing, installation and use is selected. Multifunctional processes are included using system expansion. The charging strategies at different scales including considered electricity supply is summarized in Table 2.

<i>Scale</i>	<i>Micro</i>	<i>Mezzo</i>	<i>Macro</i>
<i>Description</i>	Household	Industrial side	Belgium
<i>LCA method</i>	ALCA	ALCA	CLCA
<i>Uni-directional</i>	<ul style="list-style-type: none"> • PV • Grid 	<ul style="list-style-type: none"> • PV • Grid 	<ul style="list-style-type: none"> • Electricity supply BE 2050
<i>Uni-directional</i>	<ul style="list-style-type: none"> • PV • Grid • BESS 	<ul style="list-style-type: none"> • PV • Grid • BESS 	<ul style="list-style-type: none"> • Electricity supply BE 2050 • BESS
<i>Smart</i>	<ul style="list-style-type: none"> • PV • Grid • BESS 	<ul style="list-style-type: none"> • PV • Grid • BESS 	<ul style="list-style-type: none"> • Electricity supply BE 2050 • BESS
<i>Bi-directional</i>	<ul style="list-style-type: none"> • PV • Grid • EV battery 	<ul style="list-style-type: none"> • PV • Grid • EV batteries 	<ul style="list-style-type: none"> • Electricity supply BE 2050 • EV batteries

Table 2: System description of the four different charging strategies for the three different scales including LCA method and installed technologies (LCA = life cycle assessment, ALCA = attributional LCA, CLCA = consequential LCA, PV = photovoltaic installation, BESS = stationary battery storage, EV = electric vehicle, BE = Belgium).

4. Method

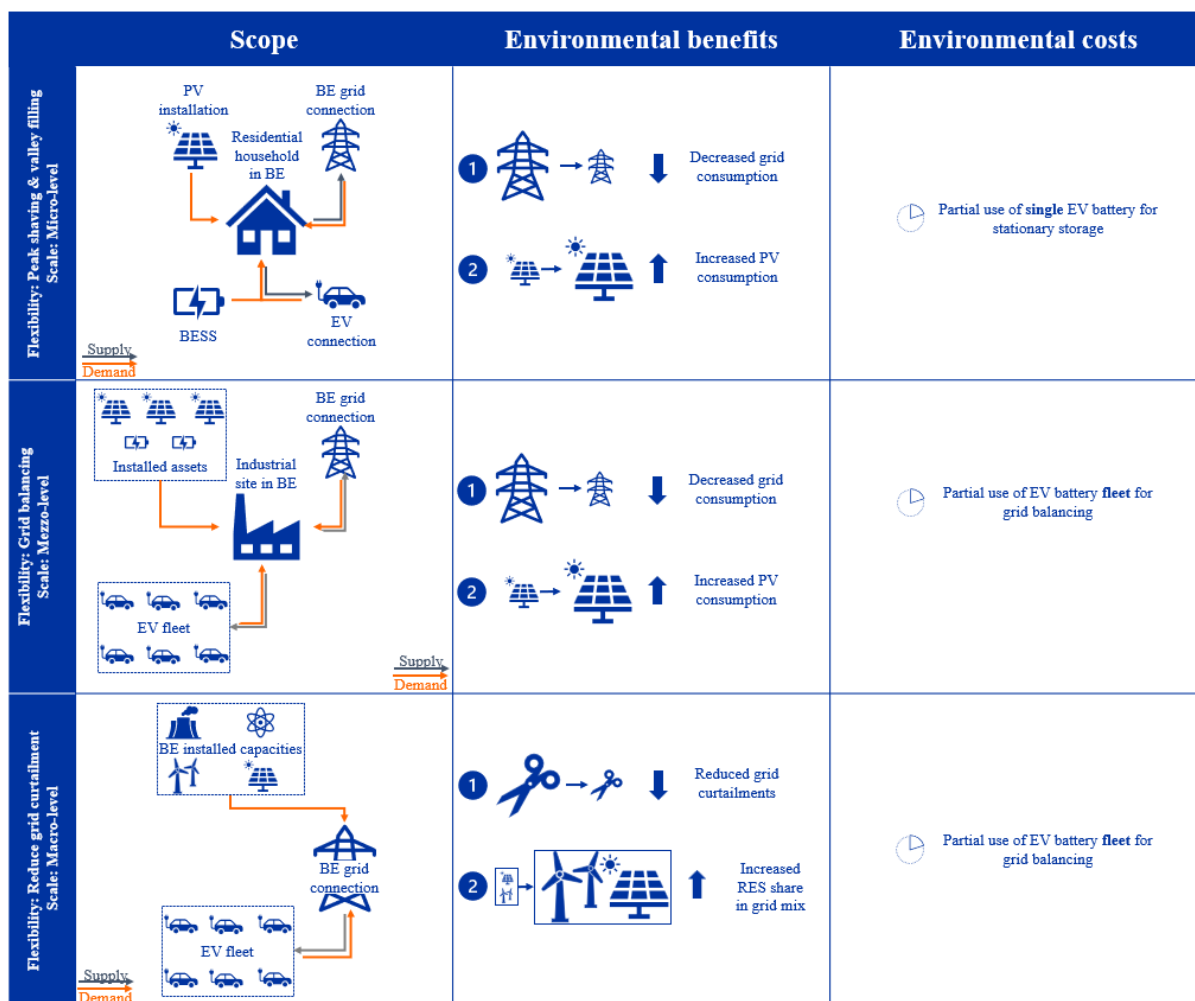


Figure 2: Overview on different use cases to assess the environmental impacts of flexibility provided by EVs on a micro-, mezzo-, and macro-level including the respective environmental system impacts (BE = Belgium, EV = electric vehicles, PV = photovoltaic, RES = renewable energy sources, BESS = stationary battery storage).

The compilation of environmental impacts at different scales considering different charging strategies is captured in Figure 2.

4.1. Micro-level assessment

To quantify whether and how much environmental impacts the micro-level system has considering different charging strategies, the CC impact at the micro-level is calculated considering PV installation and electricity supplied by the national Belgian electricity grid mix, eventually supported by BESS. The CC impact of the national Belgian electricity grid mix is calculated applying equation (1):

$$CC_{GRID}^{MICRO} = \left(\sum CC_{GRID}(n) \times \sum D_{GRID}^{MICRO}(n) \right) * LT_{TOTAL} \quad (1)$$

where:

- CC_{GRID}^{MICRO} is the total CC of the national Belgian electricity grid mix over system lifetime (gCO₂eq).
- $CC_{GRID}(n)$ is the CC impact of the Belgian grid at a given hour n (gCO₂eq/kWh).
- $D_{GRID}^{MICRO}(n)$ is the consumed grid electricity at hour n (kWh).
- LT_{TOTAL} is the system lifetime assumed in this LCA in years.

The CC impact of the PV installations can be calculated following equation **Error! Reference source not found.**):

$$CC_{iPV}^{MICRO} = S_{iPV}^{MICRO} \times CC_{PV} \times \frac{LT_{TOTAL}}{LT_{PV}} \quad (2)$$

where:

- CC_{iPV}^{MICRO} is the CC of the PV installation at the micro-level use case for charging strategy i (gCO₂eq).
- S_{iPV}^{MICRO} is the size of the PV installation at the micro-level use case when providing charging service i (kWp).
- CC_{PV} is the CC of the PV installation (gCO₂eq/kWh).
- LT_{PV} is the lifetime of the PV installation (years).

For some charging strategies, the installation of a BESS is foreseen, in particular for standard uni-directional and smart charging. The CC of manufacturing the BESS can be determined applying equation (3):

$$CC_{iBESS}^{MICRO} = S_{iBESS}^{MICRO} \times CC_{BESS} \times \frac{LT_{TOTAL}}{LT_{BESS}} \quad (3)$$

where:

- CC_{iBESS}^{MICRO} is the CC of manufacturing a BESS for charging strategy i (gCO₂eq).
- S_{iBESS}^{MICRO} is the size of the BESS for a micro-level use case where charging service i are provided (kWh capacity).
- CC_{BESS} is the CC of manufacturing a BESS (gCO₂eq/kWh capacity).
- LT_{BESS} is the lifetime of the BESS (years).

To allocate the impact on CC of the EV battery's manufacturing to driving and stationary storage, a physical allocation based on delivered electricity for stationary storage and driving over the battery's lifetime is determined. Data of electricity charged and discharged is obtained from an VUB internal developed design and optimization framework (DOF), which is explained in section 5. The allocation factor is computed with equation (4):

$$AF_{FLEX} = \frac{E_{FLEX}}{E_{DRIVING} + E_{FLEX}} \quad (4)$$

where:

- AF_{FLEX} is the allocation factor for providing flexibility services (%).
- E_{FLEX} is the discharged electricity for providing flexibility services from the battery of an EV (kWh/year)
- $E_{DRIVING}$ is the discharged electricity for powering the EV (kWh/year)

Now, the CC of the EV battery can be determined using the allocation factor as described in equation **Error! Reference source not found.**):

$$CC_{EVB}^{MICRO} = S_{EVB}^{MICRO} \times CC_{EVB} \times AF_{FLEX} \times \frac{LT_{TOTAL}}{LT_{EVB}} \quad (5)$$

where:

- CC_{EVB}^{MICRO} is the CC of the battery installed in an EV in the micro-level use case (gCO₂eq).
- S_{EVB}^{MICRO} is the size of one battery installed in an EV (kWh capacity).
- CC_{EVB} is the CC of the battery installed in an EV (gCO₂eq/kWh).
- LT_{EVB} is the calendric lifetime of the battery installed in an EV (years).

Next, equations (1) to (5) are summarized to obtain the total impact on CC of the micro-level when considering various charging strategies:

$$CC_i^{MICRO} = CC_{GRID}^{MICRO} + CC_{iPV}^{MICRO} + CC_{iBESS}^{MICRO} + CC_{EVB}^{MICRO} \quad (6)$$

where:

- CC_i^{MICRO} is the CC in the micro-level use case considering different charging strategies i (gCO₂eq).

For comparison reasons, the CC impact is then converted to its functional unit via equation (7):

$$U_i^{MICRO} = \frac{CC_i^{MICRO}}{D_{MICRO} \times LT_{TOTAL}} \quad (7)$$

where:

- U_i^{MICRO} is the CC of the micro-level use case when providing different charging services i (gCO₂eq/kWh)
- D_{MICRO} is the demanded electricity of the household per year (kWh/year).

4.2. Mezzo-level assessment

The mezzo-level use case differs from the micro-level use case by its scale: due to a higher electricity consumption, the assets increase in size, more electricity supplied by the national Belgian electricity grid mix is consumed and various EVs are considered at this scale. The same equations (1) - (7) are applied to identify the environmental impacts at the mezzo-level, allowing to draw conclusion related to upscaling of the investigated scale. Again, CC impacts of the mezzo-level is expressed in the functional unit of kWh generated electricity using equation (7).

4.3. Macro-level assessment

In macro-level use case, an energy system model called EnergyPLAN is used to update the original consequentialecoinvent database 3.9.1 electricity mix for Belgium [28]. Thus, the CC impact of the updated Belgian electricity mix can be calculated following equation (8):

$$CC_{MACRO} = \sum_T (O_T^Y \times CC_T) \quad (8)$$

where:

- CC_{MACRO} is the CC impact of the Belgian electricity grid mix incorporating EVs providing flexibility services (gCO₂eq/kWh).
- O_T^Y is the production of a certain technology T in the marginal mix in year Y (kWh).
- CC_T is the CC impact of electricity produced from technology T (gCO₂eq/kWh).

To conduct a CLCA, the relevant input and output of processes need to be modelled in a way to represent the changes in the system if the demand changes. Therefore, the marginal suppliers have to be identified and included. The terminology “marginal suppliers” is used differently in energy science and LCA. While the marginal suppliers of an energy system refers to mix of energy technologies supplying electricity at a certain time, marginal supplier definition in

CLCA is slightly different. In CLCA, marginal suppliers are the suppliers responding to an increase in demand as they are the suppliers with the lowest production costs, meaning the most competitive suppliers. According to ISO 14049, the marginal, unconstrained supplier is the modern, competitive supplier in case of increasing product demand [29]. As the focus is on electricity at low voltage, an increasing market is assumed. Modelling electricity at low voltage includes the impacts on transmission and distribution along with occurring losses. To identify the marginal long-term electricity mix, it is required to determine the annual growth rate of a future energy system, minus the capital replacement rate considering each technology lifetime [30]. First, the difference in electricity production per year is determined using equation (9):

$$D_Y = \frac{\Delta E_T}{\Delta E_Y} \quad (9)$$

where:

- D_Y is the difference in electricity production per year (TWh/year).
- $\Delta E_T = E_T^{2050} - E_T^{2023}$ is the change in electricity production per technology T (TWh).
- $\Delta E_Y = 2050 - 2023$ is the time difference in years (years).

Hereafter, the annual growth rate is obtained from equation (10):

$$T_Y = \frac{D_Y}{E_T^{2023}} \quad (10)$$

where:

- T_Y is the annual growth rate (%).
- E_T^{2023} is the electricity production per technology T in 2023 (TWh).

Next, the capital replacement rate is defined in equation (11):

$$I_T = LT_T^{-1} \quad (11)$$

where:

- I_T is the capital replacement rate per technology T (years).

Afterwards, the net annual growth rate can be determined following equation (12):

$$L_T^Y = T_Y + I_T \quad (12)$$

where:

- L_T^Y is the net annual growth rate per year Y and technology T (%).

In this context, a negative net growth rate represents an old technology and is thus not considered as a marginal supplier. Contrary, a positive net growth rate is reflecting a modern technology and therefore can be considered as potential marginal supplier. Consequently, the net annual growth can be calculated as following:

$$M_T^Y = E_T^Y \times L_T^Y \quad (13)$$

where:

- M_T^Y is the net annual growth rate per technology T in a given year (TWh/year)
- E_T^Y is the produced electricity per technology T in a given year (TWh/year)

Finally, the share per technology of the long-term marginal supply mix can be defined applying equation (14):

$$N_T^Y = \frac{M_T^Y}{\sum_T M_T^Y} \quad (14)$$

where:

- N_T^Y is the production per technology T in the marginal supply mix per kWh in year Y (kWh).
- $\sum_T M_T^Y$ is the sum of the net annual growth rate of all technologies in year Y (kWh).

The electricity mix of the different scenarios will then include the technologies with a positive, net annual growth rates [28]–[31].

Next, the ecoinvent database is consulted. For this study, the dataset “market for electricity, high voltage {BE}”, “market for electricity, medium voltage {BE}” and “market for electricity, low voltage {BE}” of the consequential ecoinvent database 3.9.1 are modified [28]. First, the supplying technologies are updated to represent the marginal supply mix of future energy systems in Belgium. Two main modifications of the original datasets of the consequential ecoinvent datasets are undertaken: first, technologies identified as constrained suppliers are removed from the market datasets. Second, the quantities of each marginal supplier are adjusted. For both steps, the EnergyPLAN model in combination with data about the PATHS2050 scenarios, containing three different future energy projections for Belgium, is applied [32].

The modification of the datasets is operationalized using python package Brightway version 2.4.3 [33]. The original ecoinvent datasets for high, medium and low voltage are stored in a new dictionary and the exchanges are updated by the output of the EnergyPLAN model. Consequently, three updated datasets for low voltage level in Belgium are created per charging strategy. Environmental impacts are quantified in terms of CC impact, using the Environmental Footprint version 3.1 methodology [34].

5. Data

Due to a scope with limited amount of assets, instead of using available life cycle inventory (LCI) data, the LCI of this study for the micro- and macro-level use case are modelled. Therefore, data for the Belgian electricity grid mix, the PV installations and BESS are collected from literature. Reasons for choosing other LCI data instead of data from well-recognized databases such as for example ecoinvent are depending on the technology: for the Belgian grid electricity mix, only an average value is available in ecoinvent. Using the CC method of the EF v3.1 results in an average of 206 gCO_{2eq}/kWh, whereas CC impact from the electricity map varies between 36 and 372 gCO_{2eq}/kWh, making up an average of 170 gCO_{2eq}/kWh in 2023 [35]. Moreover, as the objective of this study is to understand trade-offs per hour over one year, a higher time resolution than annual average values is needed. For this reason, the 'dynamic LCA model' proposed by Naumann et al. (2024) is adjusted for Belgium [36]. In this approach, the authors calculate hourly CC impact of the German electricity grid mix, taking into account imports and exports from neighbouring countries. Additionally, their approach is normalized over five years to represent a generic year neglecting unique events such as the COVID time or the natural gas crises. The underlying data are also obtained from the Transparency Platform of the European Network of Transmission System Operators for Electricity (ENTSO-E). Three dataset per country (Belgium and its importing/exporting countries) are obtained: the hourly-resolved actual generation per production type, the installed capacity per production type in annual resolution and the cross-border physical flows in hourly resolution [37]. As a result, the hourly CC impact per hourly timestep for the Belgium electricity consumption mix is calculated.

Secondly, instead of using existing datasets from ecoinvent for PV installations, the LCI data for PV installations are extracted from a report of the International Energy Agency under the title 'Methodology Guidelines on Life Cycle Assessment of Photovoltaic' [38]. Supported by a yearly PV energy production of 2,996.39 kWh for a 3 kWp PV installation in Brussels, which

is obtained from Photovoltaic Geographical Information System (PVGIS), the CC impact per kilowatt hour of produced electricity is determined [39]. The lifetime of the si-based PV installations is estimated to be 30 years [40]. Outdated data, e.g. efficiencies dating back to 2005 in the PV generated electricity datasets of the ecoinvent database or updated production locations is one main reason for remodelling the installations [28], [41]. Multi-Silicon PV installations with a capacity of 3kWp are included, as this technology represents the dominating PV technology for small scale installations according to ecoinvent [28].

For BESS, only lead acid stationary batteries are available in ecoinvent, whereas all lithium-ion battery datasets are for mobile applications [28]. According to the International Energy Agency, the dominant technology for BESS 2022 remained lithium-ion battery. Due to the absence of lithium-ion BESS in ecoinvent, LCI data are used from Le Varlet et al. (2020) [42]. Furthermore, Le Varlet et al. (2020) identifies lithium iron phosphate (LFP) as one of the most represented BESS technologies. Therefore, the mobile battery LCI modified by Le Varlet et al. (2020) of LFP battery are used in this work.

The energy system of the micro- and mezzo-level use case is sized and optimized by applying the VUB's internally developed design and optimization framework [43]. To simulate and optimize the design and operation of the micro- and mezzo-level use cases is the aim of this framework, considering different electric assets. The centrepiece of the virtual platform is an energy system simulator, modelling state-of-the-art assets based on literature and specifically developed models. The first step is to identify the optimal asset sizes by characterizing the power dispatch in a given time period. In this context, the objective function is the minimization of total system costs, accounting for investment and operating costs. After defining the minimization objective, the problem is framed as a mixed integer linear problem. The output of the design optimization framework is a design and operation optimization for the micro- and mezzo-level energy systems. The optimization can be customized to represent local conditions, such as weather data, specific electricity tariffs and investment cost via a configuration generator. A more comprehensive description of the design and optimization framework is described in Felice et al. (2022) [43].

For the micro-level use case, a random consumption profile is extracted out of 1,300 quarter-hourly consumption profiles from the Belgian network operator Fluvius [44]. The annual electricity consumption of the extracted profile is 3,897.83 kWh in 2023, supported by simulations with a low and a high consumption profile of 1,262.95 kWh and 15,990.47 kWh

in 2023. Additionally, three different EV charging profiles are generated for this case study [45]. The remaining data for running the design and optimization framework are listed in Table 3.

<i>Parameter</i>	<i>Unit</i>	<i>Low_CAPEX</i>	<i>High_CAPEX</i>	<i>EV_2</i>	<i>EV_3</i>	<i>Low_ consumption</i>	<i>High_ consumption</i>
<i>Reference year</i>	Year			2023			
<i>Charging type</i>	Text			1. Uni-directional charging without BESS 2. Uni-directional charging with BESS 3. Smart uni-directional charging with BESS 4. Bi-directional charging without BESS			
<i>Average CC impact electricity grid mix</i>	gCO ₂ eq/kWh			152			
<i>Electricity price</i>	€/kWh			0.37			
<i>CAPEX PV</i>	€/kWp	500	1,000	500	500	500	500
<i>OPEX PV</i>	€/kWp			7.50			
<i>Lifetime PV</i>	Years			25			
<i>Location</i>	Long/Lat			4; 51			
<i>Orientation</i>	Azimut(°)			90			
<i>Slope</i>	Tilt(°)			15			
<i>BEV capacity</i>	kWh			80.30			
<i>Charge-discharge efficiency</i>	%			95			
<i>Charger capacity</i>	Power (kW)			11			

Table 3: Input values for the DOF of a micro-level use case description including EV two EV charging strategies (CC = climate change, PV = photovoltaic installations, CAPEX = capital expenditures, OPEX = operational expenditures, BEV = battery electric vehicle).

6. Conclusion and outlook

In this deliverable, existing literature about environmental impacts of EVs providing flexibility services is analysed. Afterwards, a comprehensive assessment framework is presented taking into account three different scales and charging strategies. Within this framework, a novel methodology to identify environmental system impacts of flexibility services and standard unidirectional EV charging at a micro-, mezzo- and macro-level is presented. Finally, required data is presented highlighting the need for adjustment to the presented methodology.

To determine the environmental impacts of EVs providing flexibility services at different scales, the next step is to first model the energy systems of the different use cases to conduct an LCA afterwards. Once results are available, they are compared to results of existing studies as presented in Section 2. After compiling and validating the final results, the herein presented work together with the results published in an international peer-reviewed journal. In 2025, the social impact assessment will be started.

Bibliography

- [1] B. K. Sovacool, J. Axsen, and W. Kempton, “The Future Promise of Vehicle-to-Grid (V2G) Integration: A Sociotechnical Review and Research Agenda,” *Annu. Rev. Environ. Resour.*, vol. 42, no. 1, pp. 377–406, Oct. 2017, doi: 10.1146/annurev-environ-030117-020220.
- [2] M. Messagie *et al.*, “Environmental performance of a battery electric vehicle: A descriptive Life Cycle Assessment approach,” *World Electr. Veh. J.*, vol. 4, no. 1, pp. 782–786, 2011, doi: 10.3390/wevj4040782.
- [3] M. S. Koroma, N. Brown, G. Cardellini, and M. Messagie, “Prospective Environmental Impacts of Passenger Cars under Different Energy and Steel Production Scenarios,” *Energies*, vol. 13, no. 23. 2020, doi: 10.3390/en13236236.
- [4] T. R. Hawkins, B. Singh, G. Majeau-Bettez, and A. H. Strømman, “Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles,” *J. Ind. Ecol.*, vol. 17, no. 1, 2013, doi: 10.1111/j.1530-9290.2012.00532.x.
- [5] M. Messagie, F.-S. Boureima, T. Coosemans, C. Macharis, and J. V Mierlo, “A range-based vehicle life cycle assessment incorporating variability in the environmental assessment of different vehicle technologies and fuels,” *Energies*, vol. 7, no. 3, pp. 1467–1482, 2014, doi: 10.3390/en7031467.
- [6] N. Hooftman, L. Oliveira, M. Messagie, T. Coosemans, and J. Van Mierlo, “Environmental analysis of petrol, diesel and electric passenger cars in a Belgian urban setting,” *Energies*, vol. 9, no. 2, 2016, doi: 10.3390/en9020084.
- [7] L. A.-W. Ellingsen, G. Majeau-Bettez, B. Singh, A. K. Srivastava, L. O. Valøen, and A. H. Strømman, “Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack,” *J. Ind. Ecol.*, vol. 18, no. 1, pp. 113–124, Feb. 2014, doi: 10.1111/jiec.12072.
- [8] G. Majeau-Bettez, T. R. Hawkins, and A. H. Strømman, “Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles,” *Environ. Sci. Technol.*, vol. 45, no. 10, pp. 4548–4554, May 2011, doi: 10.1021/es103607c.
- [9] M. Zackrisson, L. Avellán, and J. Orlenius, “Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues,” *J. Clean. Prod.*, vol. 18,

- no. 15, pp. 1519–1529, Nov. 2010, doi: 10.1016/j.jclepro.2010.06.004.
- [10] J. F. Peters, M. Baumann, B. Zimmermann, J. Braun, and M. Weil, “The environmental impact of Li-Ion batteries and the role of key parameters – A review,” *Renew. Sustain. Energy Rev.*, vol. 67, pp. 491–506, Jan. 2017, doi: 10.1016/j.rser.2016.08.039.
- [11] M. S. Koroma *et al.*, “Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management,” *Sci. Total Environ.*, vol. 831, p. 154859, 2022, doi: <https://doi.org/10.1016/j.scitotenv.2022.154859>.
- [12] M. Lavigne Philippot *et al.*, “Life cycle assessment of a lithium-ion battery with a silicon anode for electric vehicles,” *J. Energy Storage*, vol. 60, p. 106635, 2023, doi: <https://doi.org/10.1016/j.est.2023.106635>.
- [13] M. Philippot *et al.*, “Environmental impact of the second life of an automotive battery: Reuse and repurpose based on ageing tests,” *J. Clean. Prod.*, vol. 366, pp. 1–11, Sep. 2022, doi: 10.1016/j.jclepro.2022.132872.
- [14] S. Li, C. Gu, X. Zeng, P. Zhao, X. Pei, and S. Cheng, “Vehicle-to-grid management for multi-time scale grid power balancing,” *Energy*, vol. 234, p. 121201, 2021, doi: <https://doi.org/10.1016/j.energy.2021.121201>.
- [15] C. S. Ioakimidis, D. Thomas, P. Rycerski, and K. N. Genikomsakis, “Peak shaving and valley filling of power consumption profile in non-residential buildings using an electric vehicle parking lot,” *Energy*, vol. 148, pp. 148–158, 2018, doi: <https://doi.org/10.1016/j.energy.2018.01.128>.
- [16] G. Van Kriekinge, C. De Cauwer, N. Sapountzoglou, T. Coosemans, and M. Messagie, “Peak shaving and cost minimization using model predictive control for uni- and bi-directional charging of electric vehicles,” *Energy Reports*, vol. 7, pp. 8760–8771, 2021, doi: <https://doi.org/10.1016/j.egy.2021.11.207>.
- [17] A. Goncearuc *et al.*, “The barriers to widespread adoption of vehicle-to-grid: A comprehensive review,” *Energy Reports*, vol. 12, pp. 27–41, 2024, doi: <https://doi.org/10.1016/j.egy.2024.05.075>.
- [18] L. Xu, H. Ü. Yilmaz, Z. Wang, W.-R. Poganietz, and P. Jochem, “Greenhouse gas emissions of electric vehicles in Europe considering different charging strategies,” *Transp. Res. Part D Transp. Environ.*, vol. 87, p. 102534, 2020, doi:

<https://doi.org/10.1016/j.trd.2020.102534>.

- [19] Z. Wang, P. Jochem, H. Ü. Yilmaz, and L. Xu, “Integrating vehicle-to-grid technology into energy system models: Novel methods and their impact on greenhouse gas emissions,” *J. Ind. Ecol.*, vol. 26, no. 2, pp. 392–405, Apr. 2022, doi: <https://doi.org/10.1111/jiec.13200>.
- [20] B. Nilges, C. Reinert, and N. von der Assen, “Is demand-side management environmentally beneficial? Analyzing the greenhouse gas emissions due to load shifting in electric power systems,” *J. Clean. Prod.*, vol. 434, p. 140062, 2024, doi: <https://doi.org/10.1016/j.jclepro.2023.140062>.
- [21] L. Li, D. Yang, Z. Liu, X. Ji, and N. Tomin, “Optimal Scheduling of Regional Integrated Energy System Considering the Integration of Electric Vehicles and the Life Cycle Assessment Method,” *IEEE Trans. Ind. Appl.*, vol. 60, no. 1, pp. 986–995, 2024, doi: [10.1109/TIA.2023.3285200](https://doi.org/10.1109/TIA.2023.3285200).
- [22] D. Rovelli *et al.*, “Quantification of Non-linearities in the Consequential Life Cycle Assessment of the Use Phase of Battery Electric Vehicles ,” *Frontiers in Sustainability* , vol. 2, 2021, [Online]. Available: <https://www.frontiersin.org/articles/10.3389/frsus.2021.631268>.
- [23] G. Zhao and J. Baker, “Effects on environmental impacts of introducing electric vehicle batteries as storage - A case study of the United Kingdom,” *Energy Strateg. Rev.*, vol. 40, p. 100819, 2022, doi: <https://doi.org/10.1016/j.esr.2022.100819>.
- [24] D. Wohlschlager, S. Kigle, V. Schindler, A. Neitz-Regett, and M. Fröhling, “Environmental effects of vehicle-to-grid charging in future energy systems – A prospective life cycle assessment,” *Appl. Energy*, vol. 370, p. 123618, 2024, doi: <https://doi.org/10.1016/j.apenergy.2024.123618>.
- [25] B. P. Weidema, M. Pizzol, J. Schmidt, and G. Thoma, “Attributional or consequential Life Cycle Assessment: A matter of social responsibility,” *J. Clean. Prod.*, vol. 174, pp. 305–314, 2018, doi: <https://doi.org/10.1016/j.jclepro.2017.10.340>.
- [26] R. Arvidsson *et al.*, “Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA,” *J. Ind. Ecol.*, vol. 22, no. 6, pp. 1286–1294, Dec. 2018, doi: <https://doi.org/10.1111/jiec.12690>.

- [27] International Organization for Standardization (ISO), “ISO 14040:2006. Environmental management — Life cycle assessment — Principles and framework.,” 2006, [Online]. Available: <https://www.iso.org/standard/37456.html>.
- [28] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema, “The ecoinvent database version 3 (part I): overview and methodology,” *Int. J. Life Cycle Assess.*, vol. 21, no. 9, pp. 1218–1230, Sep. 2016, doi: 10.1007/s11367-016-1087-8.
- [29] International Organization for Standardization, “ISO/TR 14049:2012 Environmental management — Life cycle assessment — Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis,” vol. 2, p. 48, 2012.
- [30] I. Muñoz and B. Weidema, “Example – marginal electricity in Denmark,” 2021. <https://consequential-lca.org/clca/marginal-suppliers/the-special-case-of-electricity/example-marginal-electricity-in-denmark/>.
- [31] B. Weidema, “Market information in life cycle assessment,” Copenhagen, 2003. [Online]. Available: <https://lca-net.com/p/1078>.
- [32] J. Correa Laguna, A. Moglianesi, P. Vingerhoets, W. Nijs, and P. Lodewijks, “PATHS 2050 - Scenarios towards a carbon-neutral Belgium by 2050,” 2023. [Online]. Available: https://perspective2050.energyville.be/sites/energyoutlook/files/inline-files/Full-Fledged_Report_1.pdf.
- [33] C. Mutel, “Brightway: An open source framework for Life Cycle Assessment,” *J. Open Source Softw.*, vol. 2, no. 12, pp. 1–2, Apr. 2017, doi: 10.21105/joss.00236.
- [34] European commission, “Environmental Footprint,” 2021. <https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html>.
- [35] Electricity Maps, “Belgium, 2023, Carbon Intensity Data,” 2023. <https://www.electricitymaps.com/data-portal>.
- [36] G. Naumann, J. Famiglietti, E. Schropp, M. Motta, and M. Gaderer, “Dynamic life cycle assessment of European electricity generation based on a retrospective approach,” *Energy Convers. Manag.*, vol. 311, p. 118520, 2024, doi: <https://doi.org/10.1016/j.enconman.2024.118520>.
- [37] ENTSO-E, “Transparency Platform,” 2023. <https://transparency.entsoe.eu/>.

- [38] R. Frischknecht, P. Stolz, G. Heath, M. Raugei, P. Sinha, and M. de Wild-Scholten, “Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity,” vol. 4th edition, pp. 1–33, 2020.
- [39] EU Science Hub, “Photovoltaic Geographical Information System (PVGIS),” 2022. https://re.jrc.ec.europa.eu/pvg_tools/en/ (accessed May 11, 2022).
- [40] V. Muteri *et al.*, “Review on life cycle assessment of solar photovoltaic panels,” *Energies*, vol. 13, no. 1. 2020, doi: 10.3390/en13010252.
- [41] J. Antonanzas and J. C. Quinn, “Net environmental impact of the PV industry from 2000-2025,” *J. Clean. Prod.*, vol. 311, p. 127791, 2021, doi: <https://doi.org/10.1016/j.jclepro.2021.127791>.
- [42] T. Le Varlet, O. Schmidt, A. Gambhir, S. Few, and I. Staffell, “Comparative life cycle assessment of lithium-ion battery chemistries for residential storage,” *J. Energy Storage*, vol. 28, pp. 1–11, Apr. 2020, doi: 10.1016/j.est.2020.101230.
- [43] A. Felice, L. Rakocevic, L. Peeters, M. Messagie, T. Coosemans, and L. Ramirez Camargo, “Renewable energy communities: Do they have a business case in Flanders?,” *Appl. Energy*, vol. 322, p. 119419, 2022, doi: <https://doi.org/10.1016/j.apenergy.2022.119419>.
- [44] Fluvius, “Digital electricity meter consumption profiles: quarter-hour values for a full year,” 2024. https://opendata.fluvius.be/explore/dataset/1_50-verbruiksprofielen-dm-elek-kwartierwaarden-voor-een-volledig-jaar/information/.
- [45] Å. L. Sørensen, K. B. Lindberg, I. Sartori, and I. Andresen, “Residential electric vehicle charging datasets from apartment buildings,” *Data Br.*, vol. 36, p. 107105, 2021, doi: <https://doi.org/10.1016/j.dib.2021.107105>.